Competition between emotional faces in visuo-spatial working memory

Marlene Poncet^{1,2}, Sara Spotorno^{1,3}, & Margaret C Jackson¹

¹ School of Psychology, University of Aberdeen, UK

² School of Psychology and Neuroscience, University of St Andrews, UK

³ Psychology Department, Durham University, UK

Abstract

Visuo-spatial working memory (VSWM) helps track the identity and location of people during social interactions. Previous work showed better VSWM when all faces at encoding displayed a happy compared to an angry expression, reflecting a prosocial preference for monitoring who was where. However, social environments are not typically uniform, and certain expressions may more strongly compete for and bias face monitoring according to valence and/or arousal properties. Here we used heterogeneous encoding displays in which two faces shared one emotion and two shared another, and asked participants to relocate a central neutral probe face after a blank delay. When considering the emotion of the probed face independently of the co-occurring emotion at encoding, an overall happy benefit was replicated. However, accuracy was modulated by the non-probed emotion, with a relocation benefit for angry over sad, happy over fearful, and sad over happy faces. These effects did not depend on encoding fixation time, stimulus arousal, perceptual similarity, or response bias. Thus, emotional competition for faces in VSWM is complex and appears to rely on

21 more than simple arousal- or valence- biased mechanisms. We propose a 'social value'

22 account to better explain when and why certain emotions may be prioritised in VSWM.

23 Keywords: face perception; visuo-spatial working memory; emotion; eye movements

24

25 Working memory (WM) plays an important role in our everyday life. It is a core component
26 of multiple cognitive functions allowing us to retain, manipulate, update, and retrieve
27 information according to the current situation (Baddeley, 2007). Signals evoking emotions
28 are particularly relevant for updating information and adapting one's behaviour
29 appropriately during social interactions. Visuo-spatial WM (VSWM), in particular, plays a
30 critical role in tracking and monitoring the identity and location of people to enable fluent
31 scene and conversation processing, both when we play an active role and during passive
32 observation. Facial expressions have been shown to influence WM for identity and location
33 information, but much of what we know is based on task displays where all faces share the
34 same emotion (Curby et al., 2019; Jackson et al., 2008, 2009, 2014; Spotorno et al., 2018).
35 In the current study, we aimed to examine how faces with differing emotional expressions
36 at encoding compete for VSWM resources to bias recall of who was where.

37 Several studies have investigated the role of facial expressions on how accurately the
38 identity of faces are encoded and maintained in WM. Their results do not always align with
39 each other and seem to depend on the specific methodology used (for reviews, see
40 Gambarota & Sessa, 2019; Xu et al., 2021). In general, in such studies participants are asked
41 to remember a set of faces and, after a short maintenance period, decide if a subsequently
42 presented (probe) face corresponds to one of the memorised face identities or not. The
43 emotional expression of the faces is irrelevant to the task but is shown to influence recall
44 accuracy. Studies that have only asked for identity recall from visual WM have found that
45 participants remember faces presented with angry expressions better than faces presented
46 with happy or neutral expressions (Jackson et al., 2008, 2009, 2014; Thomas et al., 2014). In
47 contrast, when participants are asked to recall both the identity and the location of a probe
48 face (who was where; VSWM), relocation accuracy for faces presented with a happy

49 expression was better than for faces presented with an angry expression (Spotorno et al.,
50 2018; see also Curby et al., 2019).¹

51 In the WM studies reviewed above, the stimuli were presented in an emotionally
52 homogeneous context: during the encoding stage, participants saw either one stimulus at a
53 time or multiple stimuli simultaneously, all evoking the same emotion. This is useful to
54 determine emotion effects in the absence of competition between expressions with
55 different arousal and valence properties. However, other work has shown that the
56 emotional context in which a stimulus is encoded can affect how well it is maintained in
57 memory. For example, Righi et al. (2015) asked participants to remember a happy or a
58 fearful face embedded in a happy or a fearful scene. During the retrieval phase, participants
59 were presented with a neutral face and they had to decide if its identity was shown during
60 the encoding stage. They were also asked in which of three possible scenes the face was
61 embedded. Performance was better for happy faces embedded in happy scenes, and the
62 scene (happy or fearful) was better remembered when presented with a happy face. The
63 authors interpreted this memory improvement to reflect a prosocial bias.

64 The effect of happy faces on memory performance for surrounding stimuli raises the
65 question of how simultaneously presented faces with different emotional expressions
66 compete for resources to influence recall accuracy in WM. It is well established that
67 emotional stimuli in general, including faces, compete more strongly for resources and are
68 cognitively prioritised over neutral stimuli (Compton, 2003; Vuilleumier, 2002, 2005). A few
69 studies have directly investigated resource competition in WM between differently valenced

¹ Note that we refer only to WM studies here. Tasks in which long-term memory for emotional face identities is measured tend to show happy face benefits (e.g. Chen et al., 2015; D'Argembeau & Van der Linden, 2007, 2011).

faces by comparing WM performance for neutral versus emotional faces shown together at encoding. Thomas et al. (2014) presented a single angry or happy face among three neutral faces, in a visual identity task with no spatial component. Their results showed that angry singletons were remembered better than happy singletons, replicating the angry advantage in visual WM for face identity (Jackson et al., 2008, 2009, 2014). However, WM accuracy for neutral faces was similar whether they were encoded alongside an emotional (angry or happy) singleton, or within a homogeneous display of neutral faces. That is, the authors did not find any evidence of competition in WM. If disproportionately more resources were allocated to the emotional singleton than to the neutral faces due to its strong valence, then WM for neutral faces encoded with an emotional singleton should have been worse than if the neutral faces were encoded with other neutral faces. On the other hand, Lee & Cho (2019) found that when two neutral and two emotional faces (fearful or happy) were presented simultaneously, WM performance improved for the emotional faces and decreased for the neutral faces compared to a homogeneous display in which all faces expressed the same emotion. This suggests that attentional resources in WM can be preferentially allocated to emotional over neutral faces. Interestingly, this “memory trade-off” disappeared when the faces were presented sequentially, that is, when there was less direct competition during the encoding period.

Results from a VSWM study in which both identity and location were task relevant also show some evidence that emotional information is prioritised over neutral information (Terburg et al., 2012). In this experiment, participants had to remember the identity and location of four angry or four happy faces and their four neutral counterparts that were presented with them. The faces briefly disappeared and then all reappeared at the top of the screen for participants to relocate them to their previous location in any order they

94 chose. The focus of the study was on the role of anxiety-driven biases towards or away from
95 the emotional faces, and direct statistical comparisons were not provided between
96 emotional versus neutral faces encoded in the same display. However, numerically,
97 relocation accuracy was better for happy (64.8%) than for angry (60%) faces, consistently
98 with the happy advantage found using homogeneous displays (Spotorno et al., 2018).
99 VSWM for neutral faces was also slightly poorer when they were encoded in the presence of
100 angry faces (63.5%) compared to happy faces (65.6%). Lack of direct comparisons between
101 angry and happy faces (not just with neutral), however, means that there is still insufficient
102 understanding of emotion competition effects in WM. Our current study addresses this by
103 examining for the first time how expressive faces with different emotions compete for
104 VSWM resources. This will also allow us to tease apart different theoretical accounts of such
105 competition.

106 Most WM studies using emotional faces have interpreted their results according to whether
107 face valence was positive or negative (or neutral). It has also been proposed that stimulus
108 arousal (intensity) influences WM performance. A good example of this is observed in
109 episodic memory where past events are remembered more often and with increased
110 vividness if they were highly arousing (LaBar & Cabeza, 2006). While both arousal and
111 valence information contribute to enhancing memory, they rely on distinct neural processes
112 (Kensinger & Corkin, 2004). Arousal information seems supported by the amygdala network,
113 whereas valence seems supported by the prefrontal network, although it must be noted
114 that the way in which the amygdala is activated by arousing stimuli also depends on the
115 valence of the stimuli (Mickley Steinmetz et al., 2010). Mather and Sutherland (2011)
116 developed the Arousal-Biased Competition (ABC) account, which proposes that arousal,
117 elicited internally or externally, amplifies competition between low and high priority stimuli.

118 The priority of a stimulus, as defined by Mather and Sutherland, is the combination of
119 perceptual features (visual saliency) and top-down features such as its task relevance,
120 stimulus' expectancy, or its emotional and social relevance. Depending on these factors, the
121 processing of a stimulus is either enhanced (high priority) or weakened (low priority).
122 According to the ABC account, arousal further increases this priority bias.

123 In our study, we presented only emotional faces and all four faces were task relevant, so
124 there was no strong priority bias compared to a display where both emotional and neutral
125 faces are presented or in which only some faces are task relevant. We used angry, happy,
126 sad, and fearful faces and paired these directly with one another in all possible
127 combinations. Neutral faces were not shown at encoding but were used to probe VSWM at
128 retrieval. Based on the evidence of a prosocial, happy face advantage in VSWM in
129 emotionally homogenous displays (Spotorno et al., 2018; Terburg et al., 2012), we expected
130 happy faces to be prioritised over all concurrently presented negative (angry, fear, sad)
131 faces. According to the ABC account, this effect should be stronger when happy faces are
132 paired with low arousing (sad) faces. Moreover, when all faces are negatively valenced, the
133 role of arousal may be observed more clearly, and we expected to see a VSWM advantage
134 for high arousal faces (e.g., fear) over lower arousal faces (e.g., sadness).

135 VSWM performance was assessed using the same paradigm as in Spotorno et al. (2018). We
136 measured face relocation accuracy using a categorical measure (whether the face was
137 relocated within the correct area or not) and a continuous measure (how close was it
138 relocated to the correct location). We also recorded participants' eye movements to
139 examine whether there was any systematic oculomotor behaviour dependant on the
140 emotion carried by the faces during the encoding period. More specifically, recording eye

141 movements should help us to explore the potential role of any fixation biases during the
142 encoding period in any emotional memory effects found. It has previously been shown that
143 participants fixate emotional pictures first and longer than neutral pictures (Calvo & Lang,
144 2005; Nummenmaa et al., 2006; Rösler et al., 2005; Thomas et al., 2014). For instance, in
145 Thomas et al.'s (2014) study where an angry or happy face singleton was encoded alongside
146 three neutral faces, proportionately more fixations on the angry singleton than on the
147 neutral faces resulted in poorer visual WM for neutral faces. However, previous eye-
148 movements results are not clear when positive and negative pictures are presented
149 together (Astudillo et al., 2018; Fernández-Martín & Calvo, 2016).

150 Finally, to confirm that our results were the consequence of a difference in VSWM and were
151 not due to a potential low-level perceptual or response bias, we conducted a second
152 experiment using a task that did not contain any memory component. Participants were
153 asked to match the identity of a neutral face to one of two concurrently presented
154 emotional faces used in the first experiment. If the same pattern of results is found across
155 both experiments, this would suggest that responses were biased by one type of emotion
156 regardless of the task (VSWM in Experiment 1 and perceptual identity matching task in
157 Experiment 2). Otherwise, it would confirm that the effects found in the main experiment
158 (Experiment 1) reflect the competition for resources in VSWM.

159

Experiment 1: VSWM task

Methods

Participants

Thirty-six volunteers (24 women; age: mean $\pm$ SD = 21 $\pm$ 2 years) participated in this experiment. Two additional participants were rejected, one because they did not complete the experiment, and one because their eye movements were not recorded. The experiment received the approval of the ethical committee of the School of Psychology, University of Aberdeen. All participants had normal or corrected to normal visual acuity and provided written informed consent. They were reimbursed £5 for their participation.

Even though it can be argued that some participants show poor performance, we did not reject any participant based on this criterion. The main reason is that in this experiment, accuracy depends on the size of the area that we consider as being a correct relocation (see Data analysis section) so there is no chance level per se. Instead, each participant's accuracy changes depending on the size of the correct area that we choose. In addition, it is difficult to set a threshold between "good" and "bad" performers as there is not a strict division but a continuum in accuracy performance among our group of participants.

Material

The set-up of the experiment was similar to Spotorno et al. (2018). Participants were seated in a dimly lit room with their head resting on a chinrest 40 cm away from a touchscreen computer (EliteOne 800, 1920 x 1080, screen width = 51 cm). Their eye movements were recorded using a tower mounted EyeLink 1000 Plus (SR Research) sampling at 1000 Hz. Although participants viewed the stimuli with both eyes, only their dominant eye was

recorded (the left eye for 11 participants). The face stimuli, 90 x 126 pixels, were presented on a white background using Experiment Builder (SR Research). The locations of the faces were randomly generated before the experiment, but there was always a minimum of 12° of visual angle between the centre of two faces and a central area of 7° of visual angle around the fixation cleared from any stimulus (Fig. 2). The identity, emotional expression and location of the faces were counterbalanced: twelve lists, generated in Spotorno et al. (2018), were re-used in this experiment.

We used a set of 40 grayscale face stimuli composed of eight Caucasian male individuals expressing five different emotions: neutral, happy, sad, fear and angry. The identities of the faces were the same as the ones in Spotorno et al. (2018). The faces were taken from the Radboud Faces Database (Langner et al., 2010), cropped into an oval shape (no hair was visible), set to greyscale.

The face arousal (intensity) and valence ratings provided by the Radboud Faces Database are illustrated in Fig. 1. In the Discussion, we comment on our results according to the average arousal (happy: $M_{Int} = 4.24$; angry: $M_{Int} = 3.63$; fear: $M_{Int} = 4.18$; sad: $M_{Int} = 3.18$) and valence (happy: $M_{Val} = 4.34$, sad: $M_{Val} = 2.07$, fear: $M_{Val} = 2.03$, angry: $M_{Val} = 1.98$) of each emotion. Using an average might not reflect what is happening in an individual trial, since faces with the same emotion do not always convey the same degree of arousal or valence, as this may vary depending on the specific image. However, these ratings are consistent across the different face identities so if there is a systematic bias in performance due to the arousal or valence carried by an emotion, this should be visible in the average scores per emotion regardless of the identity of the faces.

Figure 1

205

206 *Arousal and Valence Ratings of the Faces Used in the Study*

207

208 Note. The ratings, made on a 5-point scale, are taken from Langner et al. (2010). Here we show the
209 ratings for the eight face identities used in this study, across the four emotional expressions, shown at
210 encoding, plus the neutral expression, shown at retrieval.

211

212 Procedure and design

213 At the beginning of the experiment, the eye tracker was calibrated for each participant using
214 a nine-point procedure, which was then validated. Each trial started with a fixation cross
215 presented in the centre of the screen (Fig. 2). Participants had to maintain the fixation cross
216 for 300 ms within 1° of visual angle for the stimuli to be presented. Failing to do so would
217 trigger a new eye calibration. Participants were shown four to-be-remembered faces of
218 different identities at random screen locations for 6 s. To avoid any effect due to one single
219 emotion being more distinctive and better remembered (Quinlan et al., 2017), two faces
220 carried one emotion while two other faces carried a different emotion (six paired

221 combinations of angry, fear, happy, sad). After a blank (white screen) maintenance interval
222 of 1 s, one of the four faces was presented at the centre of the screen (a location never
223 occupied at encoding) with a neutral expression (probe face). Participants had to relocate
224 this probe face using the touchscreen to where it was first presented, matching the correct
225 identity with the correct location. They were asked to be as precise as possible and could
226 relocate the face as many times as they wanted before pressing the space bar to confirm
227 their response and start a new trial. It is important to note that emotion was not relevant
228 for the task, as participants were asked to remember the bound identity and location of the
229 four faces (who was where), not their expression. In all trials the probe face always shared
230 identity with one of the faces shown at encoding.

231 There was a total of 12 conditions in the experiment (six emotional pairings x two tested
232 emotion in each pairing). Each pairing condition was presented 32 times in a random order.
233 The identity of the probe face was chosen equally from one of the four faces to-be-
234 remembered. This way, the number of probe faces presented with one or the other
235 emotion at encoding was equal in each pairing condition. For example, there were 32 trials
236 with two happy and two angry faces to memorise and participants were tested on 16
237 neutral faces matching the happy identity and 16 neutral faces matching the angry identity.
238 Out of these 16 neutral faces, each face identity was presented twice. Participants were
239 trained on 12 trials and tested on a total of 192 experimental trials.

240 Participants were also asked to respond to three questionnaires as a standard procedure in
241 the lab. The first questionnaire, the Positive And Negative Affect Schedule (PANAS; Watson
242 et al., 1988) was given prior to the main experiment to measure mood at the time. The
243 second questionnaire, the Autism-Spectrum Quotient (AQ; Baron-Cohen et al., 2001) and

the third, the Liebowitz Social Anxiety Scale (LSAS; Mennin et al., 2002) were given after the memory experiment. Participants were informed that they could skip a question if they did not wish to answer it. All questionnaires were completed on the computer. Although we collected this information, we did not test any hypothesis in relation to the study presented here and so we do not report the results of the questionnaires.

Figure 2

Paradigm of the Experiment

Note. Participants had to fixate the centre of the screen for 300 ms before four emotional faces were presented on the screen (encoding period). The faces (from four identities and two emotions) were separated by a minimal distance of 12° of visual angle and an area of 7° of visual angle was left empty in the centre of the screen. After a blank interval of 1 s (maintenance period), a neutral probe face with the same identity as one of the four faces presented during the encoding period appeared in the centre of the screen. Participants had to relocate where the probe face was during the encoding period using the touchscreen (retrieval period). A response was considered correct if it was relocated within 6° of visual angle from the centre of the original location of the face. (Illustration not drawn at scale).

262 Data analysis

263 *Behavioural performance*

264 We analysed two measures of VSWM performance: accuracy and precision (Spotorno et al.,
265 2018). A response was considered correct if the probe face was relocated within a pre-
266 determined “safe zone”. This region was the original face surrounding area in which no
267 other face was presented. Here, 12° of visual angle separated two faces from centre to
268 centre, so a face was considered correctly relocated if its centre was within 6° of visual
269 angle from its original position (Fig. 2). When correctly relocated, we also measured the
270 distance between the original and relocated location (centre to centre) to obtain a measure
271 of the precision of the response within that region. We performed two types of analyses:

272 1. Overall effect of face expression on VSWM capacity. This analysis tested whether
273 VSWM performance was affected by the emotion that the neutral probe face showed at
274 encoding, irrespective of the emotion of the other faces in the display.

275 2. Competition effects. Here we examined whether and how emotions compete for
276 resources in VSWM. In this analysis, we were interested in determining if there was any
277 performance unbalance in a given emotional pairing between the relocation of one or the
278 other emotional face. To this end, we calculated the difference in relocation performance
279 for the neutral face that was presented with one emotion versus the other emotion in the
280 paired display at encoding. For example, when angry and fear faces were presented, we
281 calculated VSWM performance when the neutral face was encoded as angry versus when it
282 was encoded as fearful. We then computed the difference between these two scores and
283 compared it to 0 (which would indicate no bias in VSWM).

Statistical analysis was performed using SPSS. Because the data was skewed and therefore not normal, we used the Friedman test as a non-parametric equivalent of a repeated-measures ANOVA, to test the role of face emotion on VSWM performance². If significant, subsequent non-parametric Sign tests with Bonferroni correction for multiple comparisons were performed (all results are reported after correction by multiplying the p-values by six, which corresponds to the number of comparisons performed). We also report Kendall's coefficient of concordance (Kendall's W), which can be used as an effect size of the Friedman test (Kendall's W ranges from 0 to 1, with higher values indicating a stronger agreement among rankings). To test for a difference in performance between emotions in the biased competition analysis, we used one sample Sign tests (with a comparison to 0 for no difference). These results are also reported after Bonferroni correction by multiplying the p-values by six.

Eye movements

To determine whether participants looked longer at one or the other emotion during the encoding period, we calculated the total time spent on each face image during that time. A fixation was considered on a face stimulus if it was on or 1° of visual angle away from the oval-shaped stimulus image. After computing the time spent on each face image, we pooled the fixation time for the faces that shared the same emotion and calculated the percentage of time spent on the two emotions (equal time should be 50%). Only trials in which the total fixation time was at least 2 s (out of the 6 s encoding period) were included. We focused our

² Linear mixed models and generalised linear mixed models were applied to analyse the data published in Spotorno et al. (2018). However, in the current study, no LMM/GLMM would allow for appropriate contrasts to test the competition effects between emotions. We thus adopted a standard statistical approach.

304 analyses on fixation duration as it is a good indication of a potential emotional bias during
305 the encoding period.

306 Transparency and openness

307 All experimental programs, stimuli, data, and analysis code are publicly available on the
308 Open Science Framework (OSF) at <https://osf.io/gr96x/>. Results were analysed using
309 MATLAB (The MathWorks Inc.). All figures were created using the gramm plotting toolbox
310 (Morel, 2018). The design of the study and its analysis were not pre-registered.

311 Results

312 Overall effect of face expression on VSWM performance

313 We first tested whether the emotion of a face at encoding (angry, fear, happy or sad)
314 influenced VSWM overall regardless of the other emotion co-present at encoding. If the
315 prosocial advantage found in displays with homogeneous facial expressions (Spotorno et al.,
316 2018; Terburg et al., 2012) is also present in displays with heterogeneous emotional faces,
317 we should replicate a VSWM benefit for happy faces.

318 Accuracy: Participants were on average 67% correct in matching the identity of the probe
319 face to its original location (Fig. 3). There was a large disparity in performance: some
320 participants were very good at the task, with up to 85% correct responses while the lowest
321 performance was 19%. The results of the Friedman test showed a main effect of emotion on
322 VSWM performance (Friedman's $Q(3, N=36) = 14.71, p = .002$, Kendall's $W = 0.14$). Faces
323 encoded with a happy expression were better relocated than faces encoded with a fear
324 ($Z=3.10, p=.011$) or sad ($Z=2.83, p=.028$) expression. Moreover, sad faces were less well

relocated than fear faces ($Z=2.65$, $p=.048$). There was no other difference in performance between the other pairs of emotional expression (all $ps>0.90$).

Precision: The relocation of the probe face within the correct face region was on average 2.89° of visual angle away from the original location (Fig. 3), which is around half the distance accepted for a correct answer (6°). There was no effect of emotion on relocation precision (Friedman's $Q(3, N=36) = 4.17$, $p = .25$, Kendall's $W = 0.04$).

Figure 3

Overall VSWM Performance in Experiment 1

Note. Mean of correct relocations (a) and precision of the relocations (c) of the neutral probe face depending on the face expression at encoding, independently of the co-occurring emotion at encoding. Error bars represent SEM. Distribution of performance across participants for VSWM accuracy (b) and precision (d). The dot within each violin plot represents the median.

Swap errors: To determine the type of errors that participants made, we looked at whether some of the incorrect relocations were within another face area. This corresponds to a misbinding or swap error (Pertzov et al., 2012; Spotorno et al., 2018): participants remembered a location but reported it with a wrong face identity. This analysis revealed

that 82% of errors were swap errors, and these were not distributed similarly across the four emotions (Friedman's $Q(3, N=36) = 7.79, p = .048$, Kendall's $W = 0.07$). Participants showed a tendency for more swap errors for sad (84%) than happy (81%) or angry (80%) faces, but these effects did not survive multiple comparisons (both $ps > .13$).

Summary

Participants were overall better at relocating a face that was previously seen with a happy than a sad or fearful expression, and better at relocating a face encoded with a fearful than a sad expression. When they did not relocate the probe face accurately, participants usually exchanged a face location with another one (misbinding or swap error between face identity and location). Notably, the advantage for relocating happy faces and disadvantage for relocating sad faces matches both the pattern of valence and arousal scores with happy faces having the highest scores and sad faces the lowest (note that we are not considering direct competition effects here, rather more inherent stimulus properties). However, valence and arousal ratings do not fully explain the pattern of performance for angry and fearful faces. While these two facial expressions are both rated low in valence (i.e., negatively), fearful faces are rated higher in arousal than angry faces (Langner et al., 2010). If VSWM is better with higher arousal, we would expect better performance for fearful faces compared to angry faces. However, we found the opposite results. Thus, in general, the happy benefit found here indicates that prosocial signals may be a stronger driver than just arousal for remembering who was where.

Competition effects

VSWM performance depending on the emotion of the test face at encoding and the co-occurring emotion is presented in Table 1. To determine whether and how the emotions

carried by faces compete for resources in VSWM, we calculated the difference in performance between the two emotions presented simultaneously. No difference in performance would indicate that there is no bias between the two emotions and the stimuli are equally prioritised in VSWM. Alternatively, a difference in performance would indicate that VSWM is biased for one emotion over the other, indicating emotion-specific prioritisation of resources.

Table 1

VSWM Accuracy and Precision Depending on the Emotion of the Probe Face at Encoding and of the Other Co-occurring Emotion

Test face	Angry			Fear			Happy			Sad		
Paired emotion	Fear	Happy	Sad	Angry	Happy	Sad	Angry	Fear	Sad	Angry	Fear	Happy
Accuracy (%)	63.5	68.2	70.0	67.9	65.5	65.3	68.8	73.6	65.3	61.8	61.3	71.2
<i>SEM</i>	4.2	3.3	4.5	4.0	4.3	3.8	3.7	4.0	4.0	4.4	2.6	3.9
Precision (deg)	2.9	2.7	2.6	3.0	2.9	2.9	2.7	2.7	2.7	2.6	2.9	2.8
<i>SEM</i>	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Behavioural results

Accuracy: We first compared VSWM performance for the conditions that include happy faces to test for a potential prosocial bias (which would favour happy faces over all other negative emotions), accompanied or not by an arousal bias (which would favour happy faces when paired with any other emotion, fearful faces when paired with angry or sad faces, and angry faces when paired with sad faces). We observed better VWM performance for happy

383 faces in the happy-fear condition ($Z=3.65$, $p=.001$), showing a prosocial benefit despite
384 similar arousal levels for these two emotions (Fig 4a). However, when happy faces were
385 presented with sad faces, participants relocated the neutral probe face around 6% less
386 accurately when it matched the identity of a happy face compared to a sad face ($Z=2.68$,
387 $p=.044$). The opposite results would have been expected from a prosocial or an arousal
388 account. Furthermore, while either account would predict an advantage of happy versus
389 angry faces, there was no bias in the happy-angry condition ($Z=0.46$, $p=1$).

390 We then compared VSWM performance when two negative emotions are paired and thus
391 only considerably differ by their degree of arousal. This allows us to better isolate the role of
392 arousal in the allocation of resources in VSWM. In the angry-sad condition (Fig. 4a),
393 participants relocated the neutral probe face 8% more accurately when it matched the
394 identity of an angry face compared to a sad face ($Z=3.62$, $p=.002$); this aligns with higher
395 arousal ratings for angry than sad faces. However, no evidence for biases was found for the
396 remaining angry-fear and sad-fear pairings (all $ps>.31$); this is coherent with a valence
397 account, whereas an arousal account would instead predict an advantage for fearful faces in
398 both cases.

Precision: There was no evidence for biases in precision performance between any of the emotional pairs tested (Fig. 4b; all $ps > .21$). This suggests that emotions did not directly compete for resources in maintaining precise identity-location information.

Figure 4

Performance Bias Between Pair of Emotions in Experiment 1

Note. Absolute difference in (a) relocation accuracy, (b) precision and (c) total fixation time according to the emotion pairings presented at encoding (each boxplot represents one condition). The direction of the effect corresponds to the emotion indicated on the side of the boxplot. For example, in the happy-sad condition in (a), participants were more accurate to relocate the neutral face that was presented with a sad than with a happy expression. Similarly, in (c) the longer participants fixated on the two faces displaying one emotion, the more the boxplot deviates from 0 and towards the emotional expression that corresponds to longer fixation time (for example, happy faces were fixated longer than sad faces).

Eye movements

It is possible that participants might be looking longer at one emotion compared to the other one during the encoding period, such that some emotional faces would be encoded for longer – and thus better – than others, as information accumulates across fixations (e.g.

418 Tatler et al., 2005). This could be due to a bias in allocation of overt attention (engagement)
419 at encoding (e.g. Posner, 1980) reflecting emotion prioritisation, or to difficulties in
420 disengaging attention from some emotions, as Becker et al. (2019) found for angry faces.
421 These effects might be at the origin of the competition results that we report. We thus
422 analysed participants' fixation time on each pair of emotional faces during the encoding
423 period.

424 This analysis reveals that in each of the six pair conditions, participants spent the same
425 amount of time (50%) fixating on the two pairs of emotional faces (Fig. 4c; all $ps > .99$),
426 except when happy and sad faces were presented together. In that condition, participants
427 fixated on happy faces longer than on sad faces (51% vs. 49%, $Z=3.35$, $p=.005$; Fig. 4c).
428 Although consistent across participants, this effect is small and unlikely to be at the origin of
429 the performance bias in happy-sad displays. Indeed, we found better performance for sad
430 than for happy faces in that condition. Moreover, the other differences observed in VSWM
431 performance cannot be explained by fixation time either. Therefore, differences in VSWM
432 accuracy cannot be attributed to a difference in attentional bias either due to overt
433 engagement or disengagement during the encoding period.

434 *Summary*

435 Our results show that VSWM performance is not equal across pairs of emotion and that
436 differences in performance are not due to differences in fixation time during the encoding
437 period. This supports the idea that competition in VSWM depends on the emotion of the
438 stimulus even when emotion is not relevant for the task. However, our results cannot simply
439 be explained by differences in either valence or arousal between emotions.

440 One potential confound that we need to consider is whether our results reflect a difficulty in
441 matching the identity of the neutral probe face with that of the emotional face at encoding.
442 Indeed, applying an index which quantifies the structural similarity between images (Wang
443 et al., 2004) to the face database from Yin et al. (2006), Chen et al. (2011) showed that
444 neutral faces were structurally more similar to their sad and angry counterparts than to
445 their fearful counterparts, while neutral and happy face were structurally the least similar.
446 Thus, the degree of perceptual similarity between the neutral face in our experiment and its
447 expressive counterpart during the encoding could affect our results. Another potential
448 confound is whether any emotion effects in VSWM could be explained by a response bias in
449 reporting one emotion over another. If participants are more likely to relocate the neutral
450 face to the location of a certain emotion (regardless of whether it matches the identity of
451 the face), VSWM performance will be higher for that emotion. That is, the bias in
452 performance might be due to a difference in response bias (reporting preferentially one
453 emotion over another), not a VSWM bias. We tested these two possibilities in a second
454 experiment using the same faces as in Experiment 1, but this time no memory component
455 was involved in the task.

456 Experiment 2: Perceptual Identity Matching task

457 Participants were asked to match the identity of a neutral face with one of two concurrently
458 presented emotional faces that carried two different expressions as per the six expression
459 pairs used in Experiment 1. The identity of the neutral face always matched one of the two
460 expressive faces. If, as mentioned, the overall VSWM advantage for happy faces and
461 disadvantage for sad faces can be explained by happy faces being easier to match with a
462 neutral face and sad faces being more difficult, then accuracy and reaction times (RTs)

would be expected to be better/faster when the neutral face matches the happy face and worse/slower when the neutral face matches the sad face. We can also measure performance for each pairing conditions to assess the presence of any perceptual (matching difficulty) or response bias (reporting preferentially one emotion over another) between two emotional expressions. If these factors can explain the competition effects between pairs of emotions found in Experiment 1, we would expect to replicate better matching performance (and/or higher response bias) for angry faces in angry-sad pairs, for sad faces in sad-happy pairs and for happy faces in happy-fear pairs.

471

472 Methods

473 Participants

474 Thirty-five volunteers (29 women; age: mean $\pm$ *SD* = 19 $\pm$ 2 years) participated in this
475 experiment. Two participants were rejected from the analysis due to very poor performance
476 (d' around 0). The experiment received the approval of the ethical committee of the School
477 of Psychology, University of Aberdeen. All participants had normal or corrected to normal
478 visual acuity and provided written informed consent. They were undergraduate Psychology
479 students who completed the experiment during a group-based lab session.

480 Procedure and design

481 Participants were presented with two greyscale emotional faces, one on each side of a
482 fixation cross that was placed in the centre of a white background screen. The two faces (96
483 x 126 pixels) always carried different identities and expressions. We used the same faces as
484 in Experiment 1, with the same six possible emotion pairs (happy-angry, happy-sad, happy-

485 fear, angry-sad, angry-fear and fear-sad). After 2 s preview of the emotional face pair, a
486 neutral face appeared below the fixation cross and the face pair. Participants had to
487 determine as quickly and accurately as possible which of the emotional faces matched the
488 identity of the neutral face. Importantly, the two emotional faces and the neutral face
489 remained present together on the screen, so the task did not involve working memory but
490 purely relied on perceptual matching of face identities. The participants responded by
491 pressing one of two designated keys corresponding to the left or right located face. The
492 faces remained on the screen until a response was made. There was no feedback, and each
493 trial was self-initiated. Participants were trained on 12 trials and tested on a total of 240
494 trials (40 trials per emotion pair, presented in a random order). In each emotion pair, the
495 neutral face matched the identity of each emotional face an equal number of times (i.e.,
496 within the 40 happy-sad trials, the neutral face matched the happy face identity on 20 trials
497 and the sad face identity on 20 trials, randomised). Whether the matching face was on the
498 left or right of the face pair was also fully counterbalanced. There were no non-match trials.

499 Data analysis

500 We analysed the data by first considering the general effect of emotional expression on
501 performance regardless of the other co-occurring expression to test whether any emotional
502 expression was easier to match with the neutral face. Trials were classified depending on
503 which emotion was carried by the face that matched the identity of the neutral face. For
504 these four categories of trials (angry, fear, happy, sad), we computed accuracy (percent
505 correct) and reaction times (RT) for correct responses. As in Experiment 1, we used
506 Friedman tests to assess the role of face emotion on overall performance, followed by sign-
507 rank tests when relevant.

In a second analysis, we examined competition effects between the two emotional faces for each of the six possible emotion pairs. Unlike in Experiment 1, because there were only two possible responses (one correct and one incorrect), we were able to compute a sensitivity index (d') and a decision criterion (response bias) for each emotion pair (Green & Swets, 1966). d' was calculated as the difference in z-scores between hits and false alarms for each pairing condition separately. For example, in a pairing with an angry and a happy face, a correct match between the neutral and the angry face was considered a hit and an incorrect match (i.e., choosing the happy face) was considered a false alarm. A d' of 0 means that the number of hits was the same as the number of false alarms. Higher d' indicates better discriminability performance. Response bias was also calculated for each pairing condition separately as:

$$\text{Response criterion} = -0.5 * (z_{\text{Hits}} + z_{\text{False alarms}})$$

with the same definition for hits and false alarms as used to compute d' . A response criterion of 0 indicates no response bias; the more it deviates from 0, the higher the responses are biased. Applied to the perceptual identity-matching task, for example in the angry-happy pairing, no bias would indicate that participants are equally likely to choose the angry or the happy face. A bias different from zero, towards the happy face, would indicate that participants match preferentially the neutral face with the happy face (i.e., more often than with the angry face), regardless of the type of trial (correct or incorrect).

To test whether the neutral face is matched with one emotional expression faster than another, we also calculated the difference in RT between each paired emotional expressions for all correct responses. A difference in RT would suggest that one emotional expression is perceptually more similar to the neutral face than the other. To test this, we applied

Friedman tests on d' performance, followed by sign-rank tests when relevant. To specifically assess the presence of bias within each pairing condition, the measures of response bias and differences in RT were compared to 0 (no difference between the two emotions) using one-sample sign-tests for each pairing condition separately. All tests are reported after Bonferroni correction for multiple comparisons by multiplying p-values accordingly.

Results

Overall matching performance

To assess whether one facial emotion was easier to perceptually match with its neutral counterpart, in this analysis we focus on the effect of the emotion carried by the matching face stimulus regardless of the other emotion it was presented with (i.e., collapsed across pairing conditions). Participants' overall accuracy in matching the identity of the neutral face with its corresponding emotional face was around 90% (Fig. 5a). Accuracy performance was not equal across all emotions (Friedman's Q (3, $N=33$) =9.70, $p=.02$, Kendall's $W=0.10$) but post-hoc comparisons did not reach significance (all $ps >.07$). The analysis of RT showed that the emotion carried by the matching face did not affect the speed at which participants matched the neutral face with the correct emotional face identity (Fig. 5b; Friedman's Q (3, $N=33$) =4.40, $p=.22$, Kendall's $W=0.04$).

Figure 5

Overall Performance in Experiment 2 Using a Perceptual Identity Matching Task

Note. Mean accuracy (a) and response times (c) depending on the emotion of the face that matched the identity of the neutral face, independently of the co-occurring emotion. Error bars represent SEM. Distribution of performance across participants for accuracy (b) and RT (d). The dot within each violin plot represents the median.

Competition effects in matching performance

In this analysis, we compare performance in the perceptual identity matching task separately for the six emotional pairing conditions. Discriminability performance (d') was around 2.7 for all pairs of emotions (Fig. 6a, Friedman's Q (5, $N=33$) = 9.36, $p=.10$, Kendall's $W=0.06$). However, participants did not use the same decision criterion in all emotional pair conditions as reflected in response bias scores (Fig. 6b). Participants showed a bias towards choosing happy faces more often than angry ($Z=2.73$, $p=.038$) and towards choosing happy faces more than sad faces ($Z=2.75$, $p=.035$). Fearful faces were also chosen more likely than angry faces ($Z=3.36$, $p=.005$) in the angry-fear condition. Participants' decision criterion was not biased when matching the neutral face in the happy-fearful pairing condition ($Z=0.20$, $p=1$) or in the angry-sad pairing condition ($Z=0.36$, $p=1$). Finally, there was no significant difference in RT for correctly matching the neutral face with the identity of one of the two emotional faces depending on the pairing condition (Fig 6c; all $ps>0.28$).

Figure 6

Performance Bias Between Pair of Emotions in Experiment 2

Note. Mean discriminability (d') performance (a) and response distribution (b) in the identity matching task (Experiment 2). Error bars in (a) represent SEM. The dot in each violin plot in (b) represents the median of the distribution. Response bias (c) and RT difference (d) between each pair of emotions. The two emotions present in the display are indicated on each side of the boxplot with the vertical dashed line indicating no bias. The closer the boxplot is to the corresponding emotion label, the larger the response is biased towards this emotion and away from the other emotion in the display (for example, in (c), participants' responses are biased towards happy faces in a happy-sad pair).

Summary: In this perceptual discrimination task we did not replicate the overall pattern of effects that we found in the VSWM task in Experiment 1 (an overall advantage for happy faces and disadvantage for sad faces). Participants' performance in terms of overall accuracy and response times was very similar regardless of the emotion carried by the faces. This rejects the possibility that the overall VSWM results were due to happy faces being easier to match with the neutral face and to sad faces being harder to match with the neutral face. In terms of competition effects, performance (d' and RT) were similar across all pairs of emotional faces suggesting no difference in discriminability between the pair of emotions

that we tested. Participants showed a response bias towards selecting happy faces over angry and sad faces, and towards selecting fear faces over angry faces. These response biases in the perceptual identity matching task cannot explain the results that we found in Experiment 1 in the competition analysis (compare Fig. 4a with Fig. 6b). Specifically, the emotional pairs for which we found a competition effect in VSWM either did not show a difference in response bias (angry-sad and fear-happy) or showed the opposite effect (there was a bias in response to choose more happy than sad faces in the perceptual identity matching task, but we found better accuracy for sad than co-occurring happy faces in the VSWM task).

Taken together, the findings of the perceptual identity matching task indicate that the effects that we observed in Experiment 1 are unlikely to occur at a perceptual level. Instead, they suggest that the results from Experiment 1 are due to differences in VSWM for different emotional faces, thereby highlighting the role of emotional expression in VSWM for faces.

General Discussion

The aim of this study was to improve understanding of whether and how different emotions compete for resources and, therefore, representation in VSWM. To this purpose, we presented concurrent pairs of emotional expressions during encoding that varied in valence and arousal. Participants were asked to remember the identity and location of four emotional faces, two of which shared one emotion and the other two shared a different emotion (six emotion pairs of angry, fear, happy, and sad faces). After a short delay, one of the four faces appeared with a neutral expression and participants had to report its prior location by moving the face back to its original position using a touchscreen as precisely as

613 possible (the neutral face always shared its identity with one of the faces at encoding). To
614 perform the task accurately, participants needed to remember both the identity and
615 location of the four faces, while the emotion of the faces was irrelevant.

616 When collapsed across co-occurring emotion pairs, we found that the emotion carried by
617 the face at encoding affected participants' relocation accuracy overall but did not impact
618 relocation precision. Participants were overall best at relocating the neutral probe face to its
619 original location when it was previously seen with a happy expression, replicating the happy
620 advantage found in this task when all faces shared the same emotion at encoding (Spotorno
621 et al., 2018). We also observed lower VSWM accuracy for sad faces in general. When
622 comparing VSWM within each pair of emotion, we found better accuracy for happy over
623 fear faces, sad over happy faces, and angry over sad faces. This pattern of results is not
624 consistent with differences in either the degree of arousal or valence between the
625 emotional faces (as measured in Langner et al., 2010). Further, the time spent fixating the
626 faces during the encoding period was the same independently of the emotional expression,
627 ruling out a potential bias from a difference in encoding time. In a second experiment, we
628 tested participants in a perceptual identity matching task. The results confirmed that the
629 performance differences found in the VSWM task were not due to differences in the
630 difficulty in matching the identity of a neutral face with its emotional counterpart, or to
631 differences in response bias. We interpret our results and discuss the potential role of
632 valence and arousal in details below. We also propose a new 'social value' theory by
633 considering the more contextualised meaning of different emotions and how this may
634 influence memory for who was where.

635 Valence and Arousal accounts

636 The valence of a face modulates memory biases, with some studies showing a threat bias in
637 visual WM (Jackson et al., 2008, 2009, 2015; Thomas et al., 2014) while others showing a
638 prosocial happy face advantage in VSWM when identity-location binding is required
639 (Spotorno et al., 2018; Terburg et al., 2012). The mean valence (M_{Val}) of our stimuli was the
640 highest for happy faces ($M_{Val} = 4.34$) and around the same for the three other face
641 expressions ($M_{Val} = 2.07, 2.03, 1.98$ for sad, fear and angry faces respectively). An effect of
642 prosocial valence on VSWM for faces should, thus, predict an overall happy advantage over
643 all other emotions. The results of Experiment 1 show that VSWM performance for relocating
644 a neutral face was better overall if the face was initially encoded with a happy expression
645 compared to sad and fearful faces. This general happy advantage is consistent with previous
646 studies (Spotorno et al., 2018; Terburg et al., 2012) and indicates a prosocial advantage for
647 remembering who was where. However, we did not find a statistically significant difference
648 between angry and happy faces contrary to the happy versus angry benefit found by
649 Spotorno and colleagues. This difference might be because we showed mixed emotions
650 rather than homogenous facial expression at encoding. Indeed, when analysing
651 performance separately for each pair of emotion, relocation accuracy varied according to
652 which other emotion was present during the encoding period. In this competition analysis,
653 we found a prioritisation of happy over fearful faces but not of happy over angry or sad
654 faces. In fact, we found an opposite sad benefit over happy faces (see Fig. 4a). These
655 findings indicate that happy faces are not always prioritised in VSWM.

656 Arousal has also been suggested to affect WM performance such that highly arousing
657 stimuli are better remembered (LaBar & Cabeza, 2006). In our study, happy and fearful faces

658 had the highest average arousal, while sad faces had the lowest average arousal ratings and
659 angry faces were intermediate. Overall, we found a disadvantage in VSWM for sad faces.
660 This could be partially explained by an arousal account which proposes that low intensity
661 stimuli (sad faces in our study) are deprioritised and thus worse remembered than high
662 intensity stimuli (happy and fear faces in our study) (Mather & Sutherland, 2011). However,
663 when analysing VSWM on each emotional pair basis, the degree of arousal does not account
664 for our findings. In our experiment, we would expect the display with the largest arousal
665 disparity, i.e., for the happy and sad pairing condition, to show the highest difference in
666 VSWM performance in favour of the highest arousing (happy) faces. Our results do show a
667 significant difference in happy-sad paired displays, but in the opposite direction: low
668 arousing sad faces were better relocated. In further contradiction to an arousal-based
669 explanation, we found a) a happy bias in happy-fear displays despite little difference in
670 arousal ratings between these two emotions, and b) no competition bias in fear-sad display
671 despite a larger arousal difference between these two emotions. To sum up, the amount
672 and the direction of any differences in arousal between paired emotions did not explain
673 either the direction of the competition effects we found, or the absence of such effects.
674 Therefore, arousal of the stimuli does not solely predict VSWM performance in our
675 paradigm.

676 A 'Social Value' account

677 Most studies using heterogeneous displays for investigating the competing role of emotion
678 in WM performance have presented at encoding neutral faces together with emotional
679 faces sharing the same emotion. Their main goal was to test how performance would
680 change for the neutral stimuli depending on the emotional context they were seen in.

681 Whereas one study did not find any differences in WM performance for neutral stimuli in an
682 angry or happy context (Thomas et al., 2014), another one supports an arousal account (Lee
683 & Cho, 2019). In their study, Lee and Cho found that when emotional (fearful or happy) and
684 neutral faces were presented simultaneously, participants' WM improved for the emotional
685 faces and decreased for the neutral faces. Our study is unique as participants had to
686 remember two pairs of emotional stimuli (using angry, fear, happy and sad faces) presented
687 simultaneously, and each combination of two pairs of emotions was tested. However,
688 neither an arousal nor valence account alone can adequately support our findings.

689 We propose a 'Social Value' (SV) account to try to help unify the range of effects found here
690 and in previous research by considering how different emotional expressions evoke
691 different interpretive responses in certain circumstances. The underlying premise is that the
692 response to an emotion can vary depending on the context of the task and the task goals.
693 For example, some research has shown that the value or meaning of certain emotions
694 changes when paired with expected versus unexpected gaze direction, suggesting that
695 expressions per se do not elicit fixed interpretations and responses. Specifically, approach
696 emotions (angry and happy) are better recognised when paired with direct/approach than
697 with averted/avoidant gaze, while avoid emotions (fear) are better recognised when paired
698 with avoidant/averted than with direct/approach gaze (Adams & Kleck, 2003, 2005).
699 Modulating effects of gaze on WM for emotional faces have also been found, wherein visual
700 WM for happy face identities was significantly boosted when seen with averted than with
701 direct gaze, which may suggest that the meaning behind a smile (considered sly or
702 ambiguous with averted gaze) can be altered by other contextual features within a face
703 (Jackson, 2018). More generally, the perceived value of items has been shown to guide how
704 much they are prioritised in WM, both for non-face stimuli (Atkinson et al., 2021, 2022) and

705 for neutral faces (Thomas et al., 2016). In Thomas et al.'s study, neutral faces that were
706 imbued with a 'high value' status using monetary reward were more accurately recalled
707 from WM than faces imbued with low monetary reward. Emotional expressions can also
708 signal different values beyond intensity or valence, such as approach (happy and angry) and
709 avoid (fear) intentions (Adams & Kleck, 2003, 2005; Sander et al., 2007), and different
710 emotions elicit different behaviour: avoidance in response to anger, approach in response
711 to a smile (Marsh et al., 2005; Phaf et al., 2014). In line with this, the congruent approach
712 signal and approach behaviour properties of happy faces is suggested to have perhaps
713 elevated its value to boost VSWM in general (this study and Spotorno et al., 2018).

714 How could potential differences in social value account for the specific patterns of
715 competition effects in VSWM we found here? We can only speculate, but there may be
716 trade-offs and/or additive effects between the degree to which arousal, valence, or
717 approach-avoid properties drive the degree of prioritisation within WM in general, and
718 within this VSWM relocation task in particular. In happy-fear pairs, where a happy
719 advantage was found, the prosocial plus approach response behaviour may have elevated
720 the value of happy faces to boost participants' ability to remember the location of that
721 affiliative source. However, happy faces were deprioritised over sad or angry faces when
722 paired with them, which could in part reflect the similarity in approach signal between
723 happy and angry faces. Suggestive of more than an approach-avoid influence, sad faces
724 were significantly better relocated in sad-happy pairs. Sad expressions are shown to help
725 enhance the credibility of feelings of loss (Reed & DeScioli, 2017), so perhaps sad faces may
726 relate to a higher empathic response and thus hold increased value over happy faces to
727 boost WM for who was where. However, the role of empathy in attention and memory for
728 sad faces does not appear to be well established, so this hypothesis requires further

729 investigation. Finally, angry faces were better relocated than sad faces in angry-sad pairs,
730 which we think could suggest that negative threat signals contain greater value for
731 prioritisation and immediate source monitoring in WM than empathy-related sad faces.
732 Notably, fear was never prioritised relative to other expressions in VSWM, which could
733 reflect an avoidance response especially in a relocation task where the spatial source of the
734 original emotion signal is probed. This Social Value (SV) account has its limitations, as it
735 cannot easily explain the lack of VSWM bias in either direction for happy-angry, angry-fear,
736 and sad-fear pairs. It is likely a complex interplay of factors beyond those we have measured
737 and tried to account for here.

738 Non-WM accounts of our findings

739 The biases in VSWM performance due to the emotion of the face at encoding might be the
740 consequences of factors other than competition for resources in VSWM. One such factor
741 could be the amount of attention allocated to the different facial expressions during the
742 encoding period. Indeed, distinctive stimuli are fixated first and for a longer time, which
743 could improve their processing (Calvo & Lang, 2005; Nummenmaa et al., 2006; Rösler et al.,
744 2005; Thomas et al., 2014), and controlling for attentional resources at encoding can
745 remove differences in WM performances (Lee & Cho, 2019). The analysis of eye movements
746 in Experiment 1 (in terms of proportion of fixation time on each emotional expression) did
747 not show any strong emotional bias during the encoding period. This shows that one
748 emotional expression was not more distinctive and attention grabbing than another.
749 Importantly, happy faces were not fixated for longer than angry or fearful faces when they
750 were presented with them. This suggests that our VSWM results are unlikely to be the
751 consequence of attentional biases during the encoding period.

752 A second potential explanation for the competition effects in Experiment 1 is that they were
753 driven, at least in part, by differences in matching difficulty between the neutral face and
754 the corresponding emotional face seen during the encoding period. Indeed, it is possible
755 that neutral faces are structurally more similar to some emotional expressions than to
756 others (e.g. Chen et al., 2011), thereby biasing VSWM performance for one emotion over
757 another. However, we did not find any evidence for such effect in Experiment 2 in which no
758 memory component was required to perform the task. Participants were as accurate and
759 fast to match the neutral face to any of its emotional counterpart, and there was no
760 difference in perceptual discriminability depending on the type of emotional expressions
761 presented. Therefore, the potential difference in difficulty for matching the neutral probe
762 face with the encoded expressive face is unlikely to have affected VSWM performance.

763 A third factor that might have resulted in VSWM biases is that participants would more
764 likely relocate a face to the location of a particular emotion. The results of the perceptual
765 identity matching task in Experiment 2 did reveal that participants' response criterion was
766 not uniform across emotional faces. Participants' responses were biased away from angry
767 faces (except when paired with sad faces), which is partially in line with previous studies
768 showing that angry faces elicit an avoid behavioural response (Marsh et al., 2005; Nikitin &
769 Freund, 2019; Phaf et al., 2014; Stins et al., 2011). However, VSWM performance was not
770 lower for angry faces but even higher when paired with sad faces. Responses were also
771 biased towards happy faces in the happy-sad and happy-angry conditions. Hence, we found
772 both an attentional (fixation time) and a response bias towards happy faces in the happy-
773 sad condition across experiments. However, VSWM performance was better for sad than for
774 happy faces in this condition. Together, these results directly contradict the possibility that
775 VSWM emotional biases could be the consequence of a response bias.

776 In sum, the competition effects in VSWM that we found in Experiment 1 do not overlap with
777 potential biases in attentional resources during the encoding period or in response criterion.
778 Moreover, the difficulty to match the neutral face to its emotional counterparts was equal
779 across emotions. Thus, the effects in VSWM performance in Experiment 1 are likely the
780 results of differences in the allocation of VSWM resources depending on the emotion of the
781 faces at encoding.

782 Conclusion

783 In this study we showed that when the identity and location of emotional stimuli have to be
784 remembered and bound, VSWM is overall enhanced for happy faces (high valence and high
785 arousal stimuli) and reduced for sad faces (low valence and low arousal stimuli).
786 Importantly, we also found competition effects between some but not all pairs of emotions
787 reflected by biases in VSWM for one emotion compared to the other co-occurring emotion
788 during the encoding period. These effects were not explained by attentional, perceptual or
789 response biases, nor by the valence or arousal of the faces. Our findings highlight the need
790 to consider a more flexible system to define the potential role of emotions and their social
791 value according to the requirements and the context of the task. Our proposed Social Value
792 (SV) account is an attempt to move away from very specific and fixed expectations of
793 emotion effects in memory (also common in attention and perception fields) related to high
794 versus low arousal, positive versus negative valence, or prosocial benefits versus threat.
795 Considering how different emotions may change in 'value' (however value is defined)
796 according to different task goals and contexts will be an important step forward in
797 understanding emotion processing.

798

799 Acknowledgements

800 This research was funded by the Economic and Social Research Council (ESRC), grant
801 ES/L008912/1 to Margaret C. Jackson.

802

803 Author note

804 The results of Experiment 1 have been presented at the APS's International Convention of
805 Psychological Science (ICPS). An early version of the manuscript was deposited on PsyArXiv
806 at <https://doi.org/10.31234/osf.io/tbwkp>. All experimental programs, stimuli, data, and
807 analysis code are publicly available on the Open Science Framework (OSF) at
808 <https://osf.io/gr96x/>.

809

810 References

- 811 Adams, R. B., & Kleck, R. E. (2003). Perceived gaze direction and the processing of facial
812 displays of emotion. *Psychological Science*, 14(6), 644–647.
813 https://doi.org/10.1046/j.0956-7976.2003.psci_1479.x
- 814 Adams, R. B., & Kleck, R. E. (2005). Effects of direct and averted gaze on the perception of
815 facially communicated emotion. *Emotion (Washington, D.C.)*, 5(1), 3–11.
816 <https://doi.org/10.1037/1528-3542.5.1.3>
- 817 Astudillo, C., Muñoz, K., & Maldonado, P. E. (2018). Emotional Content Modulates
818 Attentional Visual Orientation During Free Viewing of Natural Images. *Frontiers in*
819 *Human Neuroscience*, 12, 459. <https://doi.org/10.3389/fnhum.2018.00459>

820 Atkinson, A. L., Allen, R. J., Baddeley, A. D., Hitch, G. J., & Waterman, A. H. (2021). Can
821 valuable information be prioritized in verbal working memory? *Journal of*
822 *Experimental Psychology. Learning, Memory, and Cognition*, 47(5), 747–764.
823 <https://doi.org/10.1037/xlm0000979>

824 Atkinson, A. L., Oberauer, K., Allen, R. J., & Souza, A. S. (2022). Why does the probe value
825 effect emerge in working memory? Examining the biased attentional refreshing
826 account. *Psychonomic Bulletin & Review*, 29(3), 891–900.
827 <https://doi.org/10.3758/s13423-022-02056-6>

828 Baddeley, A. (2007). *Working memory, thought, and action*. (pp. xviii, 412). Oxford
829 University Press. <https://doi.org/10.1093/acprof:oso/9780198528012.001.0001>

830 Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-
831 spectrum quotient (AQ): Evidence from Asperger syndrome/high-functioning autism,
832 males and females, scientists and mathematicians. *Journal of Autism and*
833 *Developmental Disorders*, 31(1), 5–17.

834 Becker, D. V., Rheem, H., Pick, C. M., Ko, A., & Lafko, S. R. (2019). Chapter 5 - Angry faces
835 hold attention: Evidence of attentional adhesion in two paradigms. In N. Srinivasan
836 (Ed.), *Progress in Brain Research* (Vol. 247, pp. 89–110). Elsevier.
837 <https://doi.org/10.1016/bs.pbr.2019.03.033>

838 Calvo, M. G., & Lang, P. J. (2005). Parafoveal semantic processing of emotional visual scenes.
839 *Journal of Experimental Psychology. Human Perception and Performance*, 31(3), 502–
840 519. <https://doi.org/10.1037/0096-1523.31.3.502>

841 Chen, W., Lander, K., & Liu, C. H. (2011). Matching faces with emotional expressions.
842 *Frontiers in Psychology*, 2, 206. <https://doi.org/10.3389/fpsyg.2011.00206>

843 Chen, W., Liu, C. H., Li, H., Tong, K., Ren, N., & Fu, X. (2015). Facial expression at retrieval
844 affects recognition of facial identity. *Frontiers in Psychology*, 6.
845 <https://www.frontiersin.org/articles/10.3389/fpsyg.2015.00780>

846 Compton, R. J. (2003). The interface between emotion and attention: A review of evidence
847 from psychology and neuroscience. *Behavioral and Cognitive Neuroscience Reviews*,
848 2(2), 115–129. <https://doi.org/10.1177/1534582303255278>

849 Curby, K. M., Smith, S. D., Moerel, D., & Dyson, A. (2019). The cost of facing fear: Visual
850 working memory is impaired for faces expressing fear. *British Journal of Psychology*,
851 110(2), 428–448. <https://doi.org/10.1111/bjop.12324>

852 D’Argembeau, A., & Van der Linden, M. (2007). Facial expressions of emotion influence
853 memory for facial identity in an automatic way. *Emotion*, 7(3), 507–515.
854 <https://doi.org/10.1037/1528-3542.7.3.507>

855 D’Argembeau, A., & Van der Linden, M. (2011). Influence of facial expression on memory for
856 facial identity: Effects of visual features or emotional meaning? *Emotion*
857 (*Washington, D.C.*), 11(1), 199–202. <https://doi.org/10.1037/a0022592>

858 Fernández-Martín, A., & Calvo, M. G. (2016). Selective orienting to pleasant versus
859 unpleasant visual scenes. *Cognition*, 155, 108–112.
860 <https://doi.org/10.1016/j.cognition.2016.06.010>

861 Gambarota, F., & Sessa, P. (2019). Visual Working Memory for Faces and Facial Expressions
862 as a Useful “Tool” for Understanding Social and Affective Cognition. *Frontiers in*
863 *Psychology*, 10, 2392. <https://doi.org/10.3389/fpsyg.2019.02392>

864 Green, D. M., & Swets, J. A. (1966). *Signal Detection Theory and Psychophysics* (Wiley, New
865 York).

866 Jackson, M. C. (2018). Eye gaze influences working memory for happy but not angry faces.
867 *Cognition & Emotion*, 32(4), 719–728.
868 <https://doi.org/10.1080/02699931.2017.1345720>

869 Jackson, M. C., Linden, D. E. J., & Raymond, J. E. (2014). Angry expressions strengthen the
870 encoding and maintenance of face identity representations in visual working
871 memory. *Cognition & Emotion*, 28(2), 278–297.
872 <https://doi.org/10.1080/02699931.2013.816655>

873 Jackson, M. C., Linden, D. E. J., Roberts, M. V., Kriegeskorte, N., & Haenschel, C. (2015).
874 Similarity, Not Complexity, Determines Visual Working Memory Performance.
875 *Journal of Experimental Psychology. Learning, Memory, and Cognition*.
876 <https://doi.org/10.1037/xlm0000125>

877 Jackson, M. C., Wolf, C., Johnston, S. J., Raymond, J. E., & Linden, D. E. J. (2008). Neural
878 correlates of enhanced visual short-term memory for angry faces: An fMRI study.
879 *PloS One*, 3(10), e3536. <https://doi.org/10.1371/journal.pone.0003536>

880 Jackson, M. C., Wu, C.-Y., Linden, D. E. J., & Raymond, J. E. (2009). Enhanced visual short-
881 term memory for angry faces. *Journal of Experimental Psychology. Human*
882 *Perception and Performance*, 35(2), 363–374. <https://doi.org/10.1037/a0013895>

883 Kensinger, E. A., & Corkin, S. (2004). Two routes to emotional memory: Distinct neural
884 processes for valence and arousal. *Proceedings of the National Academy of Sciences*
885 *of the United States of America*, 101(9), 3310–3315.
886 <https://doi.org/10.1073/pnas.0306408101>

887 LaBar, K. S., & Cabeza, R. (2006). Cognitive neuroscience of emotional memory. *Nature*
888 *Reviews. Neuroscience*, 7(1), 54–64. <https://doi.org/10.1038/nrn1825>

889 Langner, O., Dotsch, R., Bijlstra, G., Wigboldus, D. H. J., Hawk, S. T., & van Knippenberg, A.
890 (2010). Presentation and validation of the Radboud Faces Database. *Cognition &*
891 *Emotion*, 24(8), 1377–1388. <https://doi.org/10.1080/02699930903485076>

892 Lee, H. J., & Cho, Y. S. (2019). Memory facilitation for emotional faces: Visual working
893 memory trade-offs resulting from attentional preference for emotional facial
894 expressions. *Memory & Cognition*, 47(6), 1231–1243.
895 <https://doi.org/10.3758/s13421-019-00930-8>

896 Marsh, A. A., Ambady, N., & Kleck, R. E. (2005). The effects of fear and anger facial
897 expressions on approach- and avoidance-related behaviors. *Emotion (Washington,*
898 *D.C.)*, 5(1), 119–124. <https://doi.org/10.1037/1528-3542.5.1.119>

899 Mather, M., & Sutherland, M. R. (2011). Arousal-Biased Competition in Perception and
900 Memory. *Perspectives on Psychological Science: A Journal of the Association for*
901 *Psychological Science*, 6(2), 114–133. <https://doi.org/10.1177/1745691611400234>

902 Mennin, D. S., Fresco, D. M., Heimberg, R. G., Schneier, F. R., Davies, S. O., & Liebowitz, M. R.
903 (2002). Screening for social anxiety disorder in the clinical setting: Using the
904 Liebowitz Social Anxiety Scale. *Journal of Anxiety Disorders*, 16(6), 661–673.

905 Mickley Steinmetz, K. R., Addis, D. R., & Kensinger, E. A. (2010). The effect of arousal on the
906 emotional memory network depends on valence. *NeuroImage*, 53(1), 318–324.
907 <https://doi.org/10.1016/j.neuroimage.2010.06.015>

908 Morel, P. (2018). Gramm: Grammar of graphics plotting in Matlab. *The Journal of Open*
909 *Source Software*, 3(23), 568. <https://doi.org/10.21105/joss.00568>

910 Nikitin, J., & Freund, A. M. (2019). The Motivational Power of the Happy Face. *Brain*
911 *Sciences*, 9(1). <https://doi.org/10.3390/brainsci9010006>

912 Nummenmaa, L., Hyönä, J., & Calvo, M. G. (2006). Eye movement assessment of selective
 913 attentional capture by emotional pictures. *Emotion (Washington, D.C.)*, 6(2), 257–
 914 268. <https://doi.org/10.1037/1528-3542.6.2.257>

915 Pertzov, Y., Dong, M. Y., Peich, M.-C., & Husain, M. (2012). Forgetting What Was Where: The
 916 Fragility of Object-Location Binding. *PLoS ONE*, 7(10), e48214.
 917 <https://doi.org/10.1371/journal.pone.0048214>

918 Phaf, R. H., Mohr, S. E., Rotteveel, M., & Wicherts, J. M. (2014). Approach, avoidance, and
 919 affect: A meta-analysis of approach-avoidance tendencies in manual reaction time
 920 tasks. *Frontiers in Psychology*, 5, 378. <https://doi.org/10.3389/fpsyg.2014.00378>

921 Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*,
 922 32(1), 3–25. <https://doi.org/10.1080/00335558008248231>

923 Quinlan, P. T., Yue, Y., & Cohen, D. J. (2017). The processing of images of biological threats in
 924 visual short-term memory. *Proceedings. Biological Sciences*, 284(1861), 20171283.
 925 <https://doi.org/10.1098/rspb.2017.1283>

926 Reed, L. I., & DeScioli, P. (2017). The Communicative Function of Sad Facial Expressions.
 927 *Evolutionary Psychology: An International Journal of Evolutionary Approaches to*
 928 *Psychology and Behavior*, 15(1), 1474704917700418.
 929 <https://doi.org/10.1177/1474704917700418>

930 Righi, S., Gronchi, G., Marzi, T., Rebai, M., & Viggiano, M. P. (2015). You are that smiling guy I
 931 met at the party! Socially positive signals foster memory for identities and contexts.
 932 *Acta Psychologica*, 159, 1–7. <https://doi.org/10.1016/j.actpsy.2015.05.001>

933 Rösler, A., Ulrich, C., Billino, J., Sterzer, P., Weidauer, S., Bernhardt, T., Steinmetz, H., Frölich,
 934 L., & Kleinschmidt, A. (2005). Effects of arousing emotional scenes on the distribution
 935 of visuospatial attention: Changes with aging and early subcortical vascular

dementia. *Journal of the Neurological Sciences*, 229–230, 109–116.
<https://doi.org/10.1016/j.jns.2004.11.007>

Sander, D., Grandjean, D., Kaiser, S., Wehrle, T., & Scherer, K. R. (2007). Interaction effects of perceived gaze direction and dynamic facial expression: Evidence for appraisal theories of emotion. *European Journal of Cognitive Psychology*, 19(3), 470–480.
<https://doi.org/10.1080/09541440600757426>

Spotorno, S., Evans, M., & Jackson, M. C. (2018). Remembering who was where: A happy expression advantage for face identity-location binding in working memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, 44(9), 1365–1383.
<https://doi.org/10.1037/xlm0000522>

Stins, J. F., Roelofs, K., Villan, J., Kooijman, K., Hagenaars, M. A., & Beek, P. J. (2011). Walk to me when I smile, step back when I'm angry: Emotional faces modulate whole-body approach-avoidance behaviors. *Experimental Brain Research*, 212(4), 603–611.
<https://doi.org/10.1007/s00221-011-2767-z>

Tatler, B. W., Gilchrist, I. D., & Land, M. F. (2005). Visual memory for objects in natural scenes: From fixations to object files. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, 58(5), 931–960.
<https://doi.org/10.1080/02724980443000430>

Terburg, D., Aarts, H., & van Honk, J. (2012). Memory and attention for social threat: Anxious hypercoding-avoidance and submissive gaze aversion. *Emotion (Washington, D.C.)*, 12(4), 666–672. <https://doi.org/10.1037/a0027201>

Thomas, P. M. J., FitzGibbon, L., & Raymond, J. E. (2016). Value conditioning modulates visual working memory processes. *Journal of Experimental Psychology. Human Perception and Performance*, 42(1), 6–10. <https://doi.org/10.1037/xhp0000144>

960 Thomas, P. M. J., Jackson, M. C., & Raymond, J. E. (2014). A threatening face in the crowd:
 961 Effects of emotional singletons on visual working memory. *Journal of Experimental*
 962 *Psychology. Human Perception and Performance*, 40(1), 253–263.
 963 <https://doi.org/10.1037/a0033970>

964 Vuilleumier, P. (2002). Facial expression and selective attention. *Current Opinion in*
 965 *Psychiatry*, 15, 291–300. <https://doi.org/10.1097/00001504-200205000-00011>

966 Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention.
 967 *Trends in Cognitive Sciences*, 9(12), 585–594.
 968 <https://doi.org/10.1016/j.tics.2005.10.011>

969 Wang, Z., Bovik, A. C., Sheikh, H. R., & Simoncelli, E. P. (2004). Image Quality Assessment:
 970 From Error Visibility to Structural Similarity. *IEEE Transactions on Image Processing*,
 971 13(4), 600–612. <https://doi.org/10.1109/TIP.2003.819861>

972 Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures
 973 of positive and negative affect: The PANAS scales. *Journal of Personality and Social*
 974 *Psychology*, 54(6), 1063–1070.

975 Xu, Q., Ye, C., Gu, S., Hu, Z., Lei, Y., Li, X., Huang, L., & Liu, Q. (2021). Negative and Positive
 976 Bias for Emotional Faces: Evidence from the Attention and Working Memory
 977 Paradigms. *Neural Plasticity*, 2021, e8851066.
 978 <https://doi.org/10.1155/2021/8851066>

979 Yin, L., Wei, X., Sun, Y., Wang, J., & Rosato, M. J. (2006). A 3D facial expression database for
 980 facial behavior research. *7th International Conference on Automatic Face and*
 981 *Gesture Recognition (FGR06)*, 211–216.

982

983