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The cost of facing fear: Visual working memory is impaired for faces expressing fear

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Previous research has identified numerous factors affecting the capacity and accuracy of visual working memory (VWM). One potentially important factor is the emotionality of the stimuli to be encoded and held in VWM. We often must hold in VWM information that is emotionally charged, but much is still unknown about how the emotionality of stimuli impacts VWM performance. In the current research, we performed four studies examining the impact of fearful facial expressions on VWM for faces. Fearful expressions were found to produce a consistent cost to VWM performance. This cost was modulated by encoding time, but not set size. This cost was only present for faces in an upright orientation consistent with this cost being a product of the emotionality of the faces rather than lower-level perceptual differences between neutral and fearful faces. These findings are discussed in the context of existing theoretical accounts of the impact of emotion on information processing. We suggest that a number of competing effects drive both costs and benefits and are at play when emotional information must be stored in VWM, with the task context determining the balance between them.

Visual working memory (VWM) is a core cognitive function enabling us to temporarily keep in mind a limited number of items that are no longer visible. VWM is critical for the fluid and seamless manner in which we can function in dynamic environments. Faces experience a relatively unique advantage in VWM; VWM for faces is superior to that for other, similarly complex, object stimuli (Curby & Gauthier, 2007; but see also Curby, Glazek, & Gauthier, 2009). Faces are also relatively unique in the abundance of social and emotional information that they hold, rendering them a potentially ideal, ecologically valid stimulus for investigating how stimulus emotionality affects VWM performance. Faces expressing fear are particularly potent stimuli that have been shown to impact perception, attention, and memory and also to modulate activation across brain regions. In the current research, we examine how fearful face expressions influence VWM for faces and how different task characteristics might modulate their impact on VWM.

One possibility is that VWM for emotional, relative to neutral, faces will be enhanced through emotion's ability to modulate perceptual and attentional processes more generally. For example, there is abundant evidence at both behavioural and neural levels that emotional, relative to neutral, faces are preferentially processed, with increased

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neural activation and speeded responses to, and detection of, emotional faces (Blau, Maurer, Tottenham, & McCandliss, 2007; Hansen & Hansen, 1988; Pinkham, Griffin, Baron, Sasson, & Gur, 2010; see also Vuilleumier, 2002 for a review; Vuilleumier, Armony, Driver, & Dolan, 2003). Facial expressions signalling threat, such as fear, compared to non-threatening expressions, such as those signalling happiness, appear particularly able to gain preferential processing.

Previous findings regarding the impact of emotional expression on VWM are mixed and suggest that different emotional expressions may have distinct impacts on VWM. For example, a number of studies have reported that VWM is enhanced for faces signalling anger relative to those signalling happiness or a neutral emotional state (Jackson, Linden, & Raymond, 2014; Jackson, Wolf, Johnston, Raymond, & Linden, 2008; Jackson, Wu, Linden, & Raymond, 2009). In contrast, studies with fearful faces have found *costs* to memory performance for fearful, compared to neutral or happy, faces (Kensinger & Corkin, 2003; Maran, Sachse, & Furtner, 2015). For example, in one such study fearful expressions disrupted VWM performance, producing longer response times, but equivalent accuracy, compared to faces with neutral expressions (Kensinger & Corkin, 2003). Davis *et al.* (2011) also found a VWM performance cost for fearful faces, but in this case relative to angry faces (see also Maran *et al.*, 2015). However, in contrast with these findings, two previous studies have reported a VWM advantage, in terms of higher accuracy, for fearful faces, relative to neutral faces (Sessa, Luria, Gotler, Jolicoeur, & Dell'acqua, 2011; Stout, Shackman, & Larson, 2013). Notably, the above studies with fearful faces varied greatly in terms of their methodology. For example, the array size varied from one to fifteen items and the presentation duration ranged from 200 ms to self-timed. Thus, it is unclear what role these methodological differences played in these mixed results. A systematic study of the effects of key VWM task parameters is required to better understand the impact of fearful expressions on VWM for faces.

There is also research suggesting that different types of threatening faces, such as fearful and angry faces, have distinct impacts on the perceptual and attentional processes that support VWM. For example, fearful faces appear to be spontaneously prioritized with respect to their ability to capture attention, exhibiting a reduced susceptibility to the attentional blink compared to neutral and angry faces (Engen, Smallwood, & Singer, 2017). In addition, in this same study fearful faces were less susceptible to repetition blindness, suggesting that they may be perceptually more salient. Even under conditions where emotional signals were task-relevant, fearful faces showed evidence of greater perceptual salience and were better able to hold attention (i.e., inducing a greater attentional blink for subsequent stimuli) than did angry and neutral faces (Engen *et al.*, 2017).

Fearful faces are also relatively unique in regard to the types of threat they indicate, which can have potentially unique consequences for perception, attention, and memory. In contrast to other types of threatening faces (e.g., angry faces), which can be interpreted as directly threatening to the viewer, it has been proposed that fearful faces draw attention to contextual information in the service of disambiguating the potential threat that they indicate (Davis *et al.*, 2011). Consistent with this suggestion, the presence of a fearful face increased memory for neutral stimuli presented close in time to the fearful face, while angry faces did not, and memory for angry faces was found to be superior to that for the fearful faces (Davis *et al.*, 2011). Thus, in contrast with the VWM advantage reported for angry faces, there may instead be a cost to VWM performance for fearful faces.

One possibility that emerges from the existing varied literature is that different emotions could affect VWM at different stages of processing. Some emotional expressions may differentially influence the initial stages of attentional processing, whereas other

emotional expressions might influence post-encoding processing stages. Even more generally, emotion may have different impacts on the different subfunctions that underlie VWM. If so, then the effects of different emotional expressions might be modulated by whether the specific task conditions place greater task demands on earlier perceptual or later encoding stages of processing.

In sum, understanding the impact of stimulus emotionality on cognitive functions such as VWM is complicated by findings suggesting that stimulus emotionality can have distinct impacts on different mechanisms and stages of processing. Thus, it is unclear (1) whether such effects, if present, arise primarily via emotion's impact on early (perceptual) or late (storage and maintenance) processing stages supporting VWM performance, and (2) whether the impact of fearful expressions on VWM will be distinct from that of other expressions. Here, we first examine the impact of emotional signals of fear on VWM for faces under limited and extended encoding durations (Experiment 1), when compared to a perceptually matched (180° rotation) control condition (Experiment 2), and with small and large set sizes (Experiment 3). We then go on to directly compare VWM for faces signalling fear to those signalling other emotions (Experiments 4A and 4B).

EXPERIMENT 1

Experiment 1 assessed the impact of fearful expressions on VWM for faces. VWM for fearful and neutral faces was measured under long (4,000 ms) and short (1,000 ms) encoding times. Previous research has demonstrated that VWM for faces is constrained by perceptual limitations when short encoding times (1,000 ms) are used (Curby & Gauthier, 2007; Eng, Chen, & Jiang, 2005). Long encoding times (4,000 ms) better tap VWM capacity, unlimited by perceptual factors (Curby & Gauthier, 2007; Eng *et al.*, 2005). Thus, the use of a temporal manipulation is a first step towards better delineation of the general mechanistic locus of the basis of any differences, if present, between VWM performance for fearful and neutral faces. Specifically, an earlier prioritization or perceptual locus would be expected to produce a bigger impact of emotion with shorter encoding durations when demands on perceptual processing of the faces are greatest. In contrast, a locus in later processing stages, such as storage and maintenance, might lead to observable effects only with sufficient encoding time, and thus would produce a larger impact of emotion when ample encoding time is allowed.

Methods

Participants

Forty individuals (nine male; mean age = 20.1; *SD* = 4.9) participated for payment or course credit. All had normal or corrected-to-normal vision and provided informed consent in accordance with approval from an institutional ethics committee. Sample size was determined by a power analysis assuming a medium effect size ($\eta_p^2 = .09$).[1] This power analysis revealed that a sample size of 35 participants would be required to achieve a power level of .95 (α error probability = .05). Forty participants were recruited to compensate for the expected loss of participants due to poor performance as a result of the difficult nature of the task.

[1] *Effect sizes in previous studies investigating the effect of emotional expression on VWM are highly variable ranging from small to large so a medium effect size was chosen as the basis of the power analysis.*

Stimuli

The stimuli were 40 greyscale faces (approximately 1.3° × 1.7°) from the NimStim (Tottenham *et al.*, 2009), the Karolinska Directed Emotional Faces database (Lundqvist, Flykt, & Ohman, 1998), and the CVL Face Database (Solina, Peer, Batagelj, Juvan, & Kovac, 2003). The face images from CVL Face Database used in this work have been provided by the Computer Vision Laboratory, University of Ljubljana, Slovenia. Half the faces expressed fear and the other half wore neutral expressions. The identities of the fearful and neutral faces did not overlap.

Procedure

Participants performed a delayed match-to-sample probe recognition task simultaneously with an articulatory suppression task (to prevent participants from adopting a verbal, rather than visual, encoding strategy) (Figure 1). The study array, consisting of five faces evenly spaced in a circle (6.1° diameter), appeared for 1,000 or 4,000 ms. All the faces within a given array always had the same type of expression (e.g., neutral or fearful). After a 1,200-ms

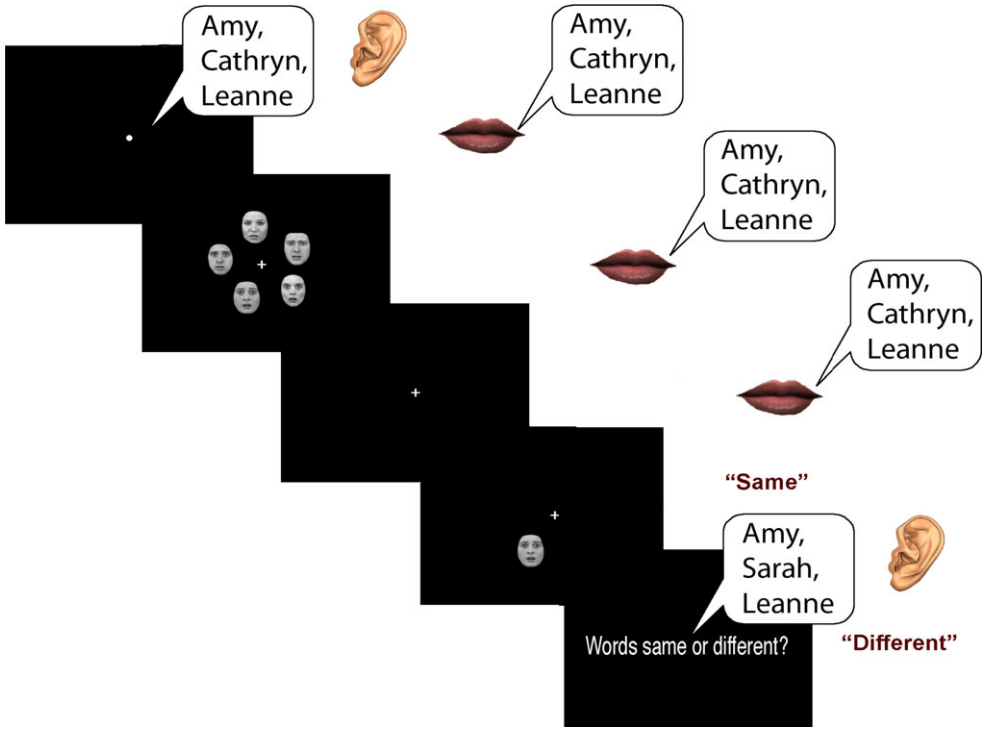

Figure 1. The sequence of events in each trial in the visual working memory (VWM) task: Participants were first presented auditorily with three names, which they overtly rehearsed throughout the trial to prevent the use of a verbal rehearsal strategy for the face task. The study array, consisting of five neutral or five fearful faces, then appeared for 1,000 or 4,000 ms. After a 1,200-ms delay, a face probe was presented in one of the locations from the study array and participants indicated whether the probe was the same as or different from the one that appeared in that location in the study array. After a response was made, three names were presented auditorily again and participants were then required to respond whether the names were the same as those they had been rehearsing throughout the trial. If they were different, only one name would be different. [Colour figure can be viewed at wileyonlinelibrary.com]

retention interval, a probe face was presented that always had the same type of expression as that shown in the study array. The probe remained until participants indicated with a key press whether the probe was the same as (50% of trials) or different from the face that had appeared in that location in the study array. To minimize confusion, within each trial the probe was never an item that had appeared at a different location in the study array.

Participants performed a total of 256 trials over 16 blocks including fearful and neutral faces (16 trials/block, randomized for presentation duration and expression). In sum, there were 128 trials for each of the two categories (fearful faces and neutral faces). For each category, there were two duration conditions, presented 64 times each.

Analysis

For each participant and condition, the number of objects successfully encoded in VWM was estimated using Cowan's *K*, where *K* = (hit rate + correct rejection rate − 1) * set size (Cowan, 2001). All analyses were performed on the *K*-scores. See Table 1 for the hit rates and correct rejection rates for each condition.

Table 1. The mean hit rates and correction rejection rates from Experiments 1–4.

Emotion	Duration (ms)	Orientation	Set size	Hit rate	Correct rejection rate
Experiment 1					
Neutral	1000	Upright	5	0.60	0.70
	4000			0.79	0.76
Fearful	1000			0.61	0.70
	4000			0.75	0.72
Experiment 2					
Neutral	1000	Upright	5	0.63	0.70
		Inverted		0.53	0.68
	4000	Upright		0.80	0.77
		Inverted		0.64	0.70
Fearful	1000	Upright		0.66	0.71
		Inverted		0.55	0.69
	4000	Upright		0.77	0.74
		Inverted		0.67	0.72
Experiment 3					
Neutral	4000	Upright	2	0.93	0.95
			4	0.82	0.84
			6	0.72	0.72
Fearful			2	0.93	0.93
			4	0.80	0.80
			6	0.72	0.70
Experiment 4a					
Neutral	4000	Upright	5	0.77	0.68
Happy				0.75	0.74
Fearful				0.69	0.70
Angry				0.73	0.68
Experiment 4b					
Neutral	4000	Inverted	5	0.72	0.57
Happy				0.75	0.60
Fearful				0.74	0.62
Angry				0.74	0.57

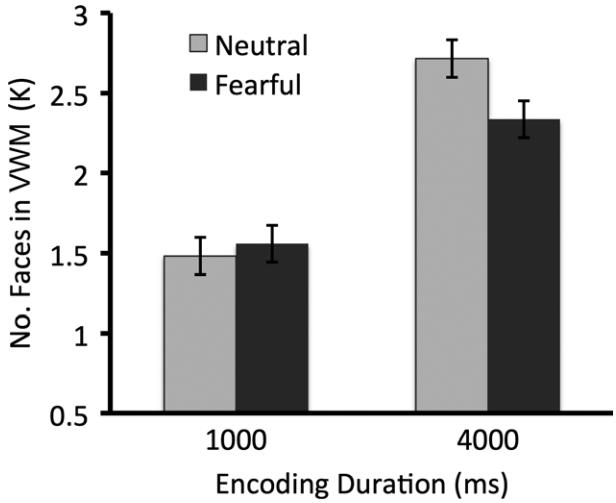

Figure 2. The number of neutral (light grey) and fearful (dark grey) faces (*K*) in visual working memory (VWM) in the 1,000-, and 4,000-ms encoding duration conditions in Experiment 1. There was a VWM cost for fearful faces, relative to neutral faces, in the long (4,000 ms) encoding duration condition. Error bars represent pooled standard error values.

Results and discussion

Data from four participants were discarded due to poor performance (overall mean $K < 1$). Incorrect articulatory suppression trials (<2.5%) were also discarded. A 2 (emotion; fearful, neutral) × 2 (encoding duration; long, short) ANOVA was performed on *K*-values calculated for each emotion and encoding duration condition for the remaining participants. This analysis failed to reveal a main effect of emotion ($F(1,35) = 2.47$, $p = .12$, $\eta_p^2 = .07$). However, there was a significant main effect of duration, $F(1,35) = 79.99$, $p \leq .0001$, $\eta_p^2 = .70$, and a significant interaction between emotion and duration, $F(1,35) = 7.71$, $p = .009$, $\eta_p^2 = .18$. Scheffé post-hoc tests revealed that this interaction was the result of a significant VWM cost for fearful over neutral faces in the long encoding duration condition ($p = .003$), but not the short encoding condition ($p = .50$) (see Figure 2). These findings suggest that, when encoding time is limited, VWM memory for faces is unaffected by the presence of a fearful facial expression. However, given sufficient encoding time, VWM for fearful faces was poorer than that for expressively neutral faces.

EXPERIMENT 2

Performance in tasks with emotional faces can be vulnerable to the impact of stimulus-level differences, unrelated to the emotionality of the stimuli. For example, in the visual search and attentional capture literature, stimulus-level features have been shown to play a significant role in what has been referred to as the angry face advantage (e.g., Becker, Anderson, Mortensen, Neufeld, & Neel, 2011). Thus, it is possible that stimulus-level differences between the fearful and neutral faces (e.g., the larger high contrast region due to the larger whites of the eyes in fearful faces), independent of the expressed emotion, could be driving the effects in Experiment 1.

The purpose of Experiment 2 was to assess whether the VWM cost for fearful faces in Experiment 1 could be explained by lower-level perceptual differences between the fearful and neutral stimuli, unrelated to the different emotional signals that they represent. Towards this end, an inverted face condition was introduced as a control. Notably, 180° in-plane rotation (inversion) disrupts access to the emotional signals in faces, while maintaining the same low-level perceptual features (e.g., Phelps, Ling, & Carrasco, 2006; Thompson, 1980). Thus, if the cost to VWM for fearful faces is a product of their emotionality, rather than lower-level perceptual differences between the fearful and neutral stimuli, inversion should eliminate this cost. In contrast, if the cost to VWM for fearful face stimuli is a product of lower-level perceptual differences between the fearful and neutral stimuli, the cost should be unaffected by inversion. The encoding duration manipulation was included again to provide an opportunity to replicate the full pattern of results from Experiment 1 and thus to assess their robustness.

Methods

Participants

To approximately match the sample size (and power) of Experiment 1, forty-one individuals (10 male; mean age = 19.9; *SD* = 2.4) were recruited and participated for payment or course credit. All had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as used in Experiment 1. In addition, inverted (i.e., 180° rotated) versions of the face stimuli were also created.

Procedure

The task was exactly the same as that used in Experiment 1, except that for each participant, half the faces were randomly assigned to appear in the upright trials, while the remaining half appeared in the inverted trials. Thus, across participants, the same stimuli appeared in the upright and inverted trials.

Participants performed a total of 256 trials over 16 alternating blocks of either upright or inverted faces. Each block included fearful and neutral faces that were presented for either 1,000 ms or 4,000 ms (16 trials/block, randomized order for presentation duration and emotional expression). In sum, there were 64 trials for each of the four stimulus categories (upright fearful, inverted fearful, upright neutral, and inverted neutral). For each category, there were two duration conditions, presented 32 times each.

Results and discussion

Data from three participants were discarded due to poor performance on the VWM task (overall mean $K < 1$). One additional participant was removed due to poor performance on the articulatory suppression task, with the remaining participants performing at a mean accuracy of 97.8%. Incorrect articulatory suppression trials were also discarded (~2% trials). A 2 (emotion; fearful, neutral) × 2 (encoding duration; long, short) × 2

(orientation; upright, inverted) ANOVA was performed on *K*-values calculated for each emotion, orientation, and encoding duration condition for the remaining participants.

This analysis failed to reveal a main effect of emotion ($F(1,36) = .32$, $p = .58$, $\eta_p^2 = .01$). However, there was a significant main effect of duration, $F(1,36) = 107.37$, $p \leq .0001$, $\eta_p^2 = .75$, and orientation, $F(1,36) = 51.36$, $p \leq .0001$, $\eta_p^2 = .59$. This was a result of better VWM performance for long, compared to short, encoding durations and upright, compared to inverted, orientations. Consistent with previous literature, Scheffé tests revealed a robust advantage for upright, over inverted, faces in both the 1,000- and 4,000-ms encoding durations; the advantage for upright faces was found for fearful and neutral faces (all ps $< .0003$; Curby & Gauthier, 2007). There were no two-way interactions present between any of the variables (all ps $> .165$). However, there was a significant three-way interaction between emotion, orientation, and duration, $F(1,36) = 4.84$, $p = .034$, $\eta_p^2 = .12$.

To investigate the basis of the three-way interaction, two-way ANOVAs were performed on the data separated by orientation. The 2 (emotion; fearful, neutral) × 2 (duration; 1,000, 4,000 ms) ANOVA on the data from the upright orientation condition revealed a main effect of duration, $F(1,36) = 61.68$, $p \leq .0001$, $\eta_p^2 = .63$, but not emotion, $F(1,36) = .28$, $p = .598$, $\eta_p^2 < .01$. VWM performance was superior in the long, compared to the short, encoding duration condition. Importantly, replicating the finding from Experiment 1, there was a significant interaction between emotion and duration, $F(1,36) = 4.65$, $p = .038$, $\eta_p^2 = .11$. Scheffé post-hoc tests failed to reveal a significant impact of fearful versus neutral expressions on face VWM in the short encoding condition (.152 K, $p = .335$), but there was a significant cost of the fearful expression (−.322 K, $p = .046$) in the long encoding condition (see Figure 3).

The 2 (emotion; fearful, neutral) × 2 (duration; 1,000, 4,000 ms) ANOVA on the data from the inverted orientation condition revealed a main effect of duration, $F(1,36) = 39.61$, $p \leq .0001$, $\eta_p^2 = .52$, with VWM performance again better in the long, compared to short, encoding duration condition. The main effect of emotion also

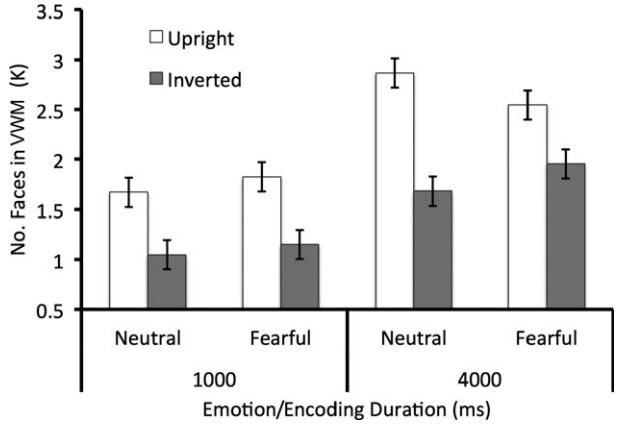

Figure 3. The number of upright (white bars) and inverted (grey bars) neutral and fearful faces (*K*) in visual working memory (VWM) in the 1,000-, and 4,000-ms encoding duration conditions in Experiment 2. As in Experiment 1, given sufficient encoding time, fearful expressions, relative to neutral expressions, produced a cost to VWM for faces. This cost was specific to upright orientations. Error bars represent pooled standard error values.

approached significance, $F(1,36) = 3.37, p = .075, \eta_p^2 = .09$), but unlike that for upright faces, this was a result of a trend for *better* VWM performance for fearful, compared to neutral, faces (see Figure 3). However, there was no interaction between duration and emotion, $F(1,36) = .367, p = .549, \eta_p^2 = .01$.

The results of Experiment 2 are consistent with those from Experiment 1. For upright faces, the impact of the emotional expression interacted with encoding duration, with fearful expressions again producing a cost to VWM performance in the long, but not short, encoding condition relative to performance with non-expressive faces. As in Experiment 1, given sufficient encoding time, VWM for fearful faces was poorer relative to that for neutral faces. Further, the cost to VWM for faces wearing fearful, compared to neutral, facial expressions is not a consequence of stimulus-level perceptual differences between the two stimulus categories; when the faces are inverted, which disrupts access to the emotional content in the faces while holding the perceptual features constant, this cost is no longer present.

EXPERIMENT 3

Previous studies reporting a VWM advantage for emotional faces typically used a smaller array or set size than was used in Experiments 1 and 2 (e.g., Linden *et al.*, 2010 and Sessa *et al.*, 2011 only presented a maximum of two faces). In addition, in other studies, observed VWM advantages for angry faces were more robust when smaller set sizes were used (Jackson *et al.*, 2009). For example, in one study the VWM benefit for angry faces over neutral faces was only present when smaller set sizes (two or three items, compared to four items) were used (Jackson *et al.*, 2008). Therefore, there might similarly be a VWM benefit for fearful faces when smaller set sizes are used, with the VWM cost for fearful faces potentially only emerging when the set size clearly exceeds the typical VWM storage capacity. To test this possibility, we manipulated the number of faces presented in the to-be-encoded arrays of neutral and fearful faces.

Emotional state has also been shown to impact the manner in which facial stimuli are processed, with negative emotional states reducing the degree to which faces are processed holistically (Curby, Johnson, & Tyson, 2012). Further, emotional state has also been shown to modulate memory recall and information processing style more generally, with evidence, across studies, that different mood states can both reduce (e.g., Figueira *et al.*, 2017) or enhance working memory performance depending on the valence of the mood state (e.g., Storbeck & Maswood, 2016). These previous studies suggest that positive and negative mood measures could be insightful for understanding the VWM cost we found for fearful faces. To explore how these individual differences between participants might contribute to the VWM cost for fearful faces, we collected self-report measures of participants' trait negative and positive affect. We also asked participants to complete a scale that provided a measure of their attentional control, as this variable has also been shown to influence performance in previous research (Derryberry & Reed, 2002). These data were collected primarily to guide future studies on the role of individual differences on VWM for emotional faces.

Participants

Eighty-two individuals (22 male; mean age = 23.3; *SD* = 5.6) participated for payment or course credit. A larger sample size, compared to Experiments 1 and 2, was collected to

support the exploratory analyses with the individual difference measures. All participants had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as those used in Experiment 2. The face stimuli represented forty separate facial identities each wearing either a neutral or a fearful expression in both an upright and inverted orientation.

Procedure

The general task procedure was similar to that used in Experiment 1 with only upright faces presented. However, instead of a duration manipulation, set size was manipulated. Two, four, or six faces appeared in the encoding array. The study array was always presented for 4,000 ms.

Participants performed a total of 192 trials over 12 alternating blocks of either upright or inverted faces. Each block showed arrays of two, four, or six faces all wearing fearful or neutral expressions (16 trials/block, randomized order for set size and emotional expression). In sum, there were 96 trials for each of the two stimulus categories (upright fearful and upright neutral), split evenly across the three set sizes, resulting in 32 trials per set size for each stimulus category.

In addition, to explore the potential relationship between the cost to VWM performance of fearful faces, individual differences in attentional control, and the experience of positive and negative affect, participants also completed the self-report Attentional Control Scale (ACS) (Derryberry & Reed, 2002) and the Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988).[2] The ACS is a widely used scale to assess an individual's control over attention. The PANAS comprises two mood scales, one that measures positive affect and another that measures negative affect. These self-report questionnaires were administered to allow exploratory analysis on the effect of these variables on the VWM cost for fearful faces. The results of these analyses may guide future studies where pre-selected, based on these variables, participant groups could be used to better probe their role.

Results and discussion

Data from three participants were discarded due to poor performance on the VWM task (overall mean $K < 1$). One additional participant was removed due to poor performance on the articulatory suppression task, with the remaining participants achieving a mean accuracy of 98.2%. Incorrect articulatory suppression trials were also discarded (<2% trials). A normalized *K*-score (*K*-norm) was calculated for each emotion condition, for each set size. This was done by not multiplying (hit rate + correct rejection rate − 1) by set size as is normally done when calculating *K*. This resulted in the scores having the same minimum and maximum range across set sizes. A 2 (emotion; fearful, neutral) × 3 (set size; 2, 4, 6) ANOVA was performed on these scores. This analysis revealed a main effect of emotion, $F(1,77) = 7.38$, $p = .008$, $\eta_p^2 = .09$, with lower VWM performance for fearful compared to neutral

[2] *These data were not collected from the first seven participants.*

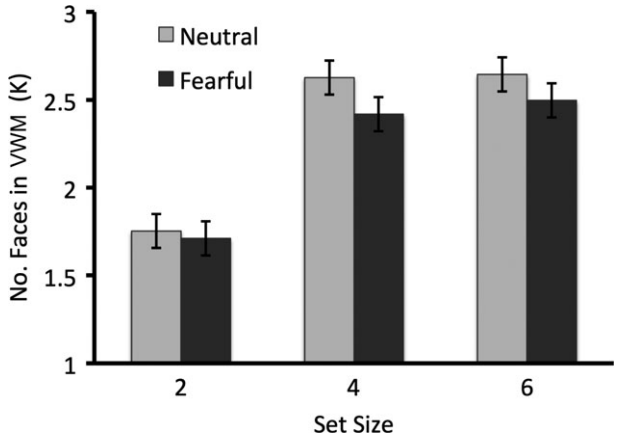

Figure 4. The number of neutral (light grey) and fearful (dark grey) faces (*K*) in visual working memory (VWM) when 2, 4, and 6 (set size) faces appeared in the study array in Experiment 3. There was a general VWM cost for fearful, relative to neutral, faces that did not interact with set size. Error bars represent pooled standard error values.

faces (see Figure 4[3]). There was also a main effect of set size, $F(1,154) = 332.9$, $p \leq .0001$, $\eta_p^2 = .82$, with the expected lower *K*-norm values when more items were presented to encode. However, there was no interaction between emotion and set size, $F(1,154) = .76$, $p = .468$, $\eta_p^2 < .01$. The relationship between the cost to VWM performance (*K*) for fearful, relative to neutral, emotional expressions and individuals' self-reported negative affect, positive affect, and attentional control was explored using Pearson correlation analyses. The relationship was assessed separately for each set size. While, the attentional control and negative affect measures failed to predict the cost of fearful expressions to VWM performance at any set size (all *p*s > .077), positive affect was able to predict this cost when the set size was large (set size 6: $r = .27$, $p = .024$; see Figure S1 in the supplementary materials) but not when it was small (set size 4: $r = .03$, $p = .80$; set size 2: $r = .03$, $p = .80$). This relationship appears to be the result of a benefit of positive affect to neutral face VWM that is eliminated when the faces are wearing fearful expressions. While a benefit of positive affect on task performance is consistent with previous research (e.g., Brose, Lovden, & Schmiedek, 2014), the elimination of this benefit for negative emotional stimuli is potentially insightful. However, given the exploratory nature of these analyses, this finding should be interpreted with caution as further studies are needed to assess the robustness of this relationship.

EXPERIMENT 4

In contrast to the results from Experiments 1, 2, and 3, where the emotional stimuli were fearful faces, a number of previous studies have revealed a VWM benefit for faces wearing

[3] *The standard* K *scores (not* K*-norms) are plotted in Figure 4 to aid comparison across the data from the different studies. Performance followed the same pattern irrespective of which* K *measure was used.*

angry expressions. It is possible that fearful expressions modulate VWM in a different manner than do other emotional expressions. To directly compare the impact of fearful expressions on VWM for faces with that of other emotional expressions, Experiments 4A (with upright faces) and 4B (with inverted faces) included neutral, happy, angry, and fearful expressions within the same study.

In addition, one methodological difference between the studies reported here and studies reporting a VWM advantage for angry faces is that these other studies used faces with the same identity across the different emotion conditions. That is, the same individual was shown wearing different facial expressions within the same study. To address the potential role of using the same identities across conditions in producing the VWM advantage for angry faces, Experiments 4A and 4B also used the same facial identities across emotion conditions.

Methods

Participants

Forty-two (30 female; mean age = 20.5; *SD* = 3.7) participants were recruited for Experiment 4A. An additional 45 (31 female; mean age; 20.2; *SD* 2.9) participants were recruited to participate in Experiment 4B.

Stimuli

The stimuli were 40 greyscale male faces (approximately 1.4° × 2.1°) from the Radboud Face Database (Langner *et al.*, 2010). Valence and intensity ratings are available for the faces in this database. These face stimuli represented ten separate identities and included an image of the same individual wearing a neutral, fearful, angry, and happy expression.

Procedure

The general task procedure was similar to that used in Experiments 1 and 2, except the presentation duration for the study array was held constant at 4,000 ms. In addition, different participants were recruited, across different studies, to complete the task with upright and inverted stimuli. With the four different emotion conditions and the long (4,000 ms) encoding duration used for all trials, the study would have been prohibitively long (~1.5 hr) if the same sample of participants had completed both the upright and inverted conditions. In previous studies, we have found that performance drops considerably when participants spend over an hour performing complex tasks, such as WM-based ones, especially when the task is made more difficult by stimulus manipulations, such as stimulus inversion for faces. Thus, participants in Experiment 4A performed the VWM task with upright faces, while those in Experiment 4B performed the same task, but with the faces in an inverted orientation.

Participants performed a total of 128 trials. Each block included faces wearing angry, fearful, happy, or neutral expressions (16 trials/block, two blocks per emotion category). In sum, there were 32 trials for each of the four stimulus categories (upright angry, upright fearful, upright happy and upright neutral). The order of the blocks was counterbalanced across participants.

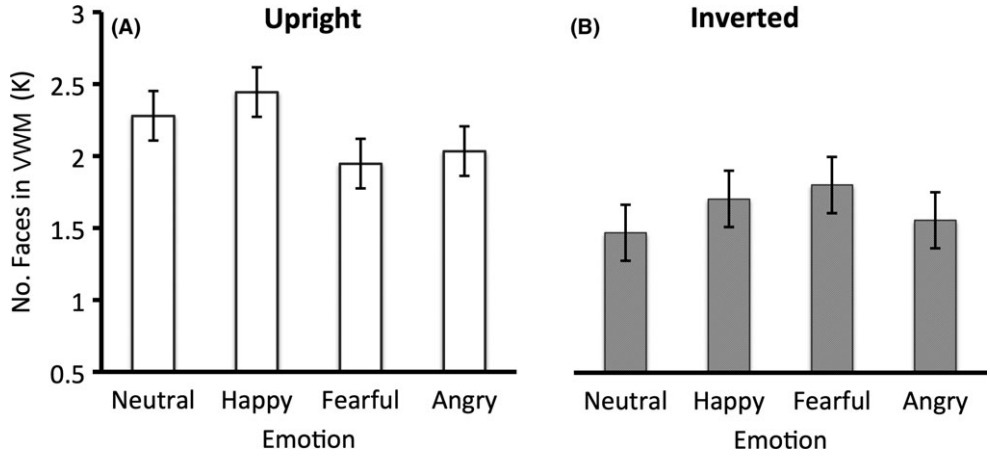

Figure 5. The number of upright (A) and inverted (B) neutral, happy, fearful, and angry faces (*K*) in visual working memory (VWM) in Experiment 4. While VWM for inverted faces wearing different expressions was similar, VWM for upright fearful and angry faces was significantly worse than that for happy faces. Error bars represent pooled standard error values.

Results and discussion

Data from two participants in the upright condition and four participants in the inverted condition were discarded due to poor performance on the VWM task (overall mean $K < .5$[4]). Two additional participants were removed due to poor performance on the articulatory suppression task, with the remaining participants achieving a mean accuracy of 98.2%. Incorrect articulatory suppression trials were also discarded (<2% trials). Forty participants remained in the upright condition and 39 in the inverted condition.

Upright faces (Experiment 4A)

An ANOVA performed on the data from Experiment 4A revealed a main effect of emotion, $F(3,117) = 3.48$, $p = .018$, $\eta_p^2 = .08$, on upright VWM performance. Planned (two-tailed) *t*-tests revealed that there was no difference between VWM performance for upright fearful and angry faces, $t(39) = .46$, $p = .65$, $d = .07$, or between happy and neutral faces, $t(39) = 1.01$, $p = .32$, $d = .16$. However, compared to VWM for happy faces, VWM was significantly worse for fearful, $t(39) = 3.14$, $p = .003$, $d = .50$, and angry faces, $t(39) = 2.33$, $p = .025$, $d = .37$ (Figure 5A). Further, there was also a marginally significant cost to VWM for fearful faces relative to neutral faces, $t(39) = 1.974$, $p = .06$, $d = .31$. However, this cost relative to neutral faces failed to reach significance for the angry face condition, $t(39) = 1.041$, $p = .17$, $d = .16$. Thus, these findings suggest that the cost to VWM is driven by the valence of the expressive faces.

[4] *The increased difficulty of the VWM task with inverted faces resulted in a much lower mean level of performance in Experiment 4B. Applying the same performance cut-offs as in the previous studies including upright faces resulted in a prohibitive proportion of participants excluded (>25%) from the inverted condition. Thus, a cut-off of a mean* K > *.5 was applied so that the proportion of participants excluded matched that of the other studies (i.e., ~10%). The same cut-off was applied for both Experiments 4A and 4B to aid comparison of the data.*

Inverted faces (Experiment 4B)

An ANOVA performed on the data from Experiment 4B failed to find support for a main effect of emotion, $F(3,114) = 1.221$, $p = .306$, $\eta_p^2 = .03$, on inverted VWM performance (Figure 5B). Planned (two-tailed) *t*-tests also revealed that there were no significant differences between VWM performance for any of the inverted conditions ($ps \geq .1$), except VWM for fearful inverted faces being marginally greater than that for neutral faces, $t(38) = 1.98$, $p = .056$, $d = .32$. Notably, this is the opposite pattern to that found for upright fearful and neutral faces in Experiment 4A, where VWM for fearful upright faces was worse than that for upright neutral faces.

Impact of emotional expression on the face inversion effect on VWM

Given that the same face stimuli were used in the upright and inverted conditions in Experiments 4A and 4B, a direct comparison of these conditions can also provide insight into the effect of emotional facial expressions on the previously documented cost of inversion for VWM for faces (Curby & Gauthier, 2007). Planned (two-tailed) *t*-tests revealed that while the classic benefit to performance when faces are presented in an upright orientation was large and statistically robust for neutral, $t(76) = 3.652$, $p = .0005$, $d = .84$, and happy faces, $t(76) = 3.444$, $p = .0009$, $d = .79$, this benefit was no longer present for fearful faces, $t(76) = .792$, $p = .43$, $d = .18$, and was only marginally present for angry faces, $t(76) = 2.017$, $p = .05$, $d = .46$. Given that inversion disrupts access to the emotional information in faces, these findings are consistent with the suggestion that negative emotional expressions, but not positive expressions, can be costly for VWM, rendering VWM for faces expressing these emotions no better than those for inverted faces. This is particularly interesting given the typical magnitude and robustness of inversion costs to face VWM (Curby & Gauthier, 2007; Curby *et al.*, 2009). However, it is worth noting that an inversion effect *was* found for VWM for fearful faces in Experiment 2. Further, given that this is a between-subjects comparison, caution needs to be applied when interpreting this absence of an inversion effect for fearful faces in Experiment 4.

Expressive face ratings

Given the qualitatively similar, but stronger, pattern of findings for the fearful faces compared to the angry faces, we examined the ratings of valence and intensity provided for the faces used in an attempt to provide insight into their relative impact. Statistical analyses (*t*-tests) comparing the mean ratings of valence and intensity for the face stimuli used (Langner *et al.*, 2010) revealed that while the angry and fearful faces were matched in terms of their rated valence (angry: $M = 2.03$, SD .27; fearful: $M = 2.14$, SD .15; $t(9) = 1.40$, $p = .20$, $d = .486$), the fearful faces were rated as having significantly greater intensity of emotion (angry $M = 3.65$, SD .52, fearful $M = 4.13$, SD .20, $t(9) = 3.27$, $p > .01$, $d = 1.28$). Thus, one possibility is that the generally weaker cost to VWM performance for angry faces than for fearful faces, relative to neutral and happy faces, may be a result of the weaker intensity of the (negative) emotional signal in these faces. Notably, inconsistent with a general intensity account, independent of valence, the happy and fearful faces were matched on intensity (happy faces, $M = 4.26$, SD .31, $t(9) = 1.22$, $p = .25$, $d = .4$). However, unsurprisingly, they were not matched on valence (happy faces, $M = 4.26$, SD .25, $t(9) = 9.53$, $p \leq .0001$, $d = 7.4$).

Meta-analysis

Given that Experiments 1 - 4 all included conditions with upright fearful and neutral faces with an array presentation duration of 4,000 ms, these data were combined in a meta-analysis.[5] This 2 (emotion: neutral, fearful) × 4 (experiment: 1, 2, 3, 4) ANOVA on the *K*-scores from each condition within each experiment revealed a main effect of emotion, $F(1,185) = 21.27$, $p \leq .0001$, with poorer VWM for fearful than neutral faces. In addition, there was a main effect of experiment, $F(3,185) = 3.59$, $p = .015$, but no interaction between the experiment and emotion effects, $F(3,185) = .378$, $p = .77$. Scheffé tests revealed that the basis of the main effect of experiment was the lower performance in Experiment 4 relative to Experiment 2 ($p = .019$), with performance in the other studies falling between, but not being significantly different to, these two extremes (all other ps $> .13$). Thus, despite variation in performance level across experiments, there was no detectable difference in the size (or presence) of the cost to VWM for faces wearing fearful expressions.

GENERAL DISCUSSION

The studies reported here provide evidence of a cost to VWM for faces expressing fear. This cost was no longer present when the stimuli were rotated 180°, consistent with the cost emerging due to the emotionality of the stimuli, rather than to featural differences, as the extraction of emotional face information is typically disrupted by 180° rotation (e.g., Phelps *et al.*, 2006; Thompson, 1980). Further, this cost was only present when the encoding time was in the range where VWM for faces is no longer limited by perceptual factors associated with their visual complexity (Curby & Gauthier, 2007; Eng *et al.*, 2005). This cost was also present when VWM for fearful faces was compared to that for happy faces, consistent with the valence of the expression, rather than more general aspects of emotionality, playing a key role in this effect. Further, we also found evidence of a similar cost to VWM for angry, relative to neutral, faces. Together, these results suggest that the cost to VWM performance for faces when they are wearing fearful expressions is not a product of perceptual difficulty and/or complexity of the fearful faces, but instead reflects a cost more directly due to the negative emotionality of the fearful faces. Here, we review relevant literature and suggest potential accounts for the cost to VWM for faces expressing fear.

Established patterns of attentional biases to threatening stimuli may be able to provide insight into our findings. These patterns include, depending on the specific task conditions, facilitated attention to, avoidance of, and difficulty disengaging from threatening stimuli (e.g., Carlson & Mujica-Parodi, 2014; Cooper & Langton, 2006; Fox, Russo, Bowles, & Dutton, 2001). Specifically, difficulty disengaging from, and increased dwell time on, threatening stimuli, such as fearful faces, may underlie the poorer VWM for fearful compared to neutral faces. This may be especially apparent when the set size is large, and the encoding duration is long, because under these conditions the task requires the participant to engage and disengage from stimuli multiple times in order to encode the full array of faces. A difficulty disengaging from threatening faces would have resulted in fewer fixations on each face within these arrays, compared to arrays of neutral faces, potentially counteracting the established benefits to face VWM performance of longer

[5] *Experiments 1 to 3 used a set size of 5. However, in Experiment 3 the set size varied. Data from the set size 4 condition were used in the meta-analysis. However, the pattern of significance remained the same when the set size 6 condition data were included instead. The same data inclusion criteria (i.e., mean K ≥ 1 and articulatory suppression task accuracy ≥85%) were applied across all data in the analysis.*

encoding durations (Curby & Gauthier, 2007). Notably, when encoding duration is short, this cost may be reduced as the limited encoding time would greatly constrain the number of times each face could be actively fixated on regardless of the emotion it is expressing. Further, when encoding time is limited, the rapid attentional bias to threatening stimuli may instead facilitate processing (e.g., Cooper & Langton, 2006), potentially resulting in the VWM benefit observed when brief (e.g., 200 ms) encoding durations are used. Notably, although these attentional biases to threatening stimuli have been predominantly documented with respect to their relationship to trait anxiety, similar patterns have been found in non-clinical populations suggesting that they may also apply, to some degree, to the processing of threatening stimuli more generally (e.g., Carlson & Mujica-Parodi, 2014; Fox *et al.*, 2000; Ohman, Lundqvist, & Esteves, 2001).

The simultaneous presentation of multiple negative emotional stimuli may have also disrupted encoding via the high demands it places on selective attention mechanisms. Specifically, if each emotional face is simultaneously competing for attention, this would likely make it difficult for selective attention to operate given that more faces are present than could be selected at any one time. This may be especially disruptive to VWM given that an important factor influencing VWM performance is the efficiency with which people can avoid encoding irrelevant information (Vogel, McCollough, & Machizawa, 2005). In addition, in the case where the amount of relevant information exceeds one's VWM capacity, the ability to attend to or select a manageable subset of information to encode is also an important factor determining VWM performance (Linke, Vicente-Grabovetsky, Mitchell, & Cusack, 2011). Thus, the simultaneous presentation of multiple emotional faces, in this case five, may have been particularly disruptive to VWM performance by making it difficult for observers to adopt the optimal strategy of selecting a subset of the stimuli. Consistent with this possibility, there is less efficient gating of task-irrelevant fearful, compared to neutral, faces from VWM (Stout *et al.*, 2013). Further, fearful faces may be particularly vulnerable to competitive interactions between stimuli given their greater perceptual salience and ability to capture attention compared to other emotional faces, such as angry faces (Engen *et al.*, 2017). Further, the larger set size used in Experiment 4, compared to that used in previous studies with angry faces reporting VWM benefits (e.g., Jackson *et al.*, 2009), would have likely increased this competition for selection, also potentially contributing to the different pattern of performance reported here. However, the absence of an interaction between set size and emotion in Experiment 3 is inconsistent with set size being the sole factor accounting for the VWM cost for fearful faces. Long encoding durations also likely play a key role, increasing the potential for interference or competitive interactions between stimuli during encoding. Thus, it is possible that the long encoding duration in Experiment 3 may have allowed for sufficient competitive interactions to occur to impair VWM for fearful faces irrespective of the array size.

It is also possible that, once encoded, the emotional nature of the stimuli may have resulted in greater interference between presentations stored in VWM. The arousal-biased competition (ABC) model suggests that the arousal-inducing nature of the expressive faces would make it more difficult to maintain multiple representations of expressive faces at the same time, as is necessary in VWM tasks (Mather & Sutherland, 2011). Specifically, this model suggests that while perception and memory for emotional stimuli are prioritized, leading to benefits in some encoding contexts, simultaneously maintaining multiple high priority representations in VWM can lead to overall suppression, with arousal increasing these mutual inhibitory effects. Thus, this model predicts that maintaining multiple emotionally charged stimuli with equal (high) priority status, such as

an array of fearful or angry faces, will result in an overall decrement in working memory performance. It is also likely that the happy (smiling) faces were only minimally arousing, given that smiling at others is as much a cultural norm as it is an expression of happiness. Further, the finding of a more robust VWM cost for fearful faces compared to angry faces, coupled with the higher ratings of intensity for fearful relative to angry faces, is consistent with this account.

Of potential relevance is the typically holistic nature of face processing, where both features and their relations are bound within a unitary representation. These holistic representations afford benefits for VWM with (neutral) faces, and other objects of expertise that are also processed holistically, showing a VWM advantage (Curby & Gauthier, 2007; Curby *et al.*, 2009). Emotion can disrupt the creation of these representations with the induction of negative emotional states disrupting holistic processing of faces (Curby *et al.*, 2012). Further, while there is an enhancement of within-object feature binding for emotional features of stimuli (for relevant reviews see Kensinger, 2009; Mather, 2007), emotional arousal appears to impair the binding of non-emotional features to these representations (Mather *et al.*, 2006). For example, the spatial location of highly arousing stimuli was remembered more poorly than that for less arousing stimuli, suggesting that the spatial location was more poorly bound to the object (Mather *et al.*, 2006). Mather *et al.* (2006) suggest that arousal recruits attention to emotional features, which then dominate encoding at the expense of other features resulting in less complete binding of features. Thus, it is possible that the arousing nature of the emotional face stimuli in the current studies may have drawn attention preferentially to the emotional features of the stimuli (i.e., the facial expression), de-emphasizing more identity-specific features of the faces, while also disrupting the creation of the typical holistic representations of the face stimuli. Given that all the to-be-encoded faces within an array had an expression from the same emotion, and thus had similar emotionally relevant features (e.g., larger whites of the eyes in fearful faces), this could have hurt performance when it came to identifying whether the target face had been present in the study array. On a related note, the interference model of VWM suggests that items that share similarity space interfere with each other in VWM (Oberauer & Lin, 2017). Emphasizing the shared emotional features, rather than the unique (identity-specific) features, across the faces within an array may have resulted in the expressive faces clustering together in a similarity space, thereby resulting in greater interference between the stored representations. However, it is unclear why happy faces would not have experienced the same potential cost due to an emphasis on their shared emotional features.

We speculate that emotional stimuli may have distinct and opposing effects on VWM subprocesses that operate on different timescales. Specifically, potential costs associated with competition and/or interference between representations in VWM may accumulate over time and increase with the number and arousal-inducing nature of the emotional stimuli simultaneously held in VWM. In contrast, previously observed facilitatory effects of emotion may operate more rapidly, potentially increasing the precision with which emotional stimuli can be encoded (Jackson *et al.*, 2014). Consistent with this possibility, the size of the VWM advantage for angry faces is reduced when longer encoding times are allowed (Jackson *et al.*, 2009), and it is eliminated when a long retention interval is used (Jackson, Linden, & Raymond, 2012). A long retention interval may allow competitive or other interference effects to accumulate to a larger degree. The larger set size and long encoding duration used in the current study may have rendered performance more susceptible to such interactions between representations than in the previous studies with angry faces. Thus, when the nature of the task is such that competitive/interference effects will dominate (e.g., long retention interval and/or larger set sizes), a cost will

emerge for emotional stimuli. In contrast, if the nature of the task is such that the facilitatory effects will dominate (or at least compensate for the competitive effects; e.g., via short retention intervals and smaller set sizes), a benefit will emerge.

It is possible that there is a tipping point that was crossed in the studies reported here, compared to previous studies reporting a VWM advantage for negatively valenced emotional faces. Specifically, long presentation durations and larger set sizes may tip the balance towards a greater influence of the impacts of emotion on later, post-perceptual, processing stages, relative to the earlier, perceptual stages. In contrast, short encoding durations would place a greater burden on earlier perceptual processes. In this case, the benefits of emotionality for perceptual processing, via increased salience and the ability to attract/hold attention, might dominate performance, potentially resulting in the VWM advantage observed in some previous studies with emotional faces. Consistent with this possibility, the studies reporting a VWM advantage for fearful faces used a small set size (one or two items) and a brief encoding duration (200 ms; Sessa *et al.*, 2011; 500 ms; Stout *et al.*, 2013). Thus, we suggest that whether the emotionality of to-be-stored stimuli results in a performance cost or benefit is determined by the task conditions under which VWM is measured.

In conclusion, the emotionality of stimuli, such as fearful faces, can impair the complex cognitive function that is VWM. Together with previous research, our findings suggest that the precise impact of fearful expressions on VWM for faces depends on a complex interplay between the array of impacts of emotionality, which includes both costs and benefits, on the different cognitive and perceptual processes that underpin VWM. Further research is needed to fully understand the different factors influencing VWM for emotionally charged stimuli, as well as the potential for meaningful distinctions between the influences of different types of emotions on VWM. Together, such studies would provide important insights into how the emotionality of stimuli can influence the fundamental cognitive processes, namely visual working memory, supporting our fluid visual experience of the world.

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Supporting Information

The following supporting information may be found in the online edition of the article:

Figure S1. The relationship between the visual working memory (VWM) cost for fearful faces and participants self-reported levels of positive affect as measured by the Positive and Negative Affect Schedule (PANAS; Watson *et al.*, 1988).