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Dual-Task Interference on Left Eye Utilization During Facial Emotion Perception

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There is an ongoing debate in the literature about whether facial emotion perception is carried automatically—that is, without effort or attentional resources. While it is generally accepted that spatial attention is necessary for the perception of emotional facial expressions, the picture is less clear for central attention. Using the bubbles method, we provide results that were obtained by measuring the effect of the psychological refractory period on diagnostic information for the basic facial expressions. Based on previous findings that linked spatial attention with processing of the eyes and of high spatial frequencies in the visual periphery, we hypothesized that reliance on the eyes might decrease when central resources were monopolized by a difficult prioritized auditory task. Central load led to a marked decrease in left eye utilization that was generalized across emotions; on the contrary, utilization of the mouth was unaffected by central load. Thus, processing of the left eye might be nonautomatic, and processing of the mouth might be automatic. Interestingly, we also observed a reduction in reliance on the left side of the face under central load that was accompanied by a commensurate increase in reliance on the right side of the face. We end with a discussion of how hemispheric asymmetries might account for these peculiar findings.

Public Significance Statement

There exists a debate regarding whether facial expressions of emotions can be perceived while cognitive resources are allocated to another process, such as in multitasking. In the present study, we look at the effect of dual tasking on the visual information processing that supports facial emotion recognition. Our data show that the processing of some information is altered under such circumstances, and therefore that it has a cognitive cost; however, this cost might differ across facial features, and also between the cerebral hemispheres.

Keywords: emotion, bubbles, psychophysics, central attention, automatic processing

With its various combinations of muscle contractions, the face can change the shape of its features to express different internal states (Ekman & Friesen, 1975; Izard, 1971), and as such, it is a staple of nonverbal communication (Jack & Schyns, 2015). Given the social and evolutionary significance of emotional facial signals, one might assume that they are perceived automatically—that is, without effort or attentional resources (e.g., Palermo & Rhodes, 2007).

The first forays into this question have investigated the effect of visual spatial attention on amygdala activation. Spatial attention operates in perceptual stages preceding identification and is used for the selection of relevant information in the visual field (Posner, 1980). Participants in such a paradigm are typically asked to endogenously direct covert attention toward a certain target feature or location and ignore distractors elsewhere in the visual field. Despite initial reports of increased amygdala activation to ignored expressive faces (e.g., Vuilleumier, Armony, Driver, & Dolan, 2001), research conducted with a more cognitively demanding main task failed to replicate this finding (Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; see also, for similar results, Alpers et al., 2009; Bishop, Jenkins, & Lawrence, 2007; Kellermann et al.,

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2012; Mitchell et al., 2007; Pessoa, Padmala, & Morland, 2005; Sebastian, McCrory, De Brito, & Viding, 2017). This indicates that visual spatial attention is necessary for at least some aspect of facial expression processing. It also illustrates the fact that it is critical, when testing for automaticity, to employ a main task that is sufficiently taxing so that it will prevent spare attentional resources from being deployed toward unattended stimuli (e.g., perceptual load model, Lavie, 1995; biased competition model, Desimone & Duncan, 1995).

More recently, some researchers have begun investigating the role of central attention in facial expression processing. Central attention is thought to operate at processing stages coinciding with or following short-term memory consolidation (e.g., Johnston, McCann, & Remington, 1995), and is used in the preferential allocation of processing resources to a specific task (Pashler, 1991). One methodological tool that is frequently used to study effects of central attention is the psychological refractory period dual-task paradigm (PRP; Pashler, 1984; Telford, 1931), whereby the overlap between the central processing stages of two tasks—a first prioritized task (T_1), and a second nonprioritized task (T_2)—is experimentally manipulated by varying the stimulus onset asynchrony (SOA). Typically, greater central overlap (i.e., shorter SOA, e.g., 300 ms) will lead to increased response times for the nonprioritized T2, compared to little or no overlap (i.e., longer SOA, e.g., 1,000 ms).

Bottleneck models of central attention may rely on locus-of-slack logic (Pashler, 1994), which consists in manipulating the difficulty of certain stages of T_2 processing and then observing how this manipulation interacts with SOA. If T_2 difficulty has an effect on T_2 response times at long, but not at short, SOA (an effect known as under additivity), then this will be taken as evidence that the manipulated stages of T_2 occurred prior to the central bottleneck. If, on the contrary, T_2 difficulty affects T_2 response times equally in both SOA conditions (an effect known as additivity), then this will be taken as evidence that the manipulated stages of T_2 occurred at or after the central bottleneck, and are therefore nonautomatic. As it currently stands, one study has relied on locus-of-slack logic to investigate facial expression perception (Tomasik, Ruthruff, Allen, & Lien, 2009). In it, subjects first discriminated between a pure tone and noise (T_1), and then discriminated between ambiguous (i.e., difficult T_2) or unambiguous (i.e., easy T_2) angry and happy expressions. T_2 additivity was observed, and thus was taken as evidence that emotion perception requires central processing.

However, the ambiguous nature of the visual stimuli might have affected later (i.e., at/after the central bottleneck) decision-making stages, instead of perceptual processing per se. To disambiguate the issue, Shaw, Lien, Ruthruff, and Allen (2011) used the N2pc electrophysiological index of visuospatial attention (Eimer, 1996; Luck & Hillyard, 1994) to determine whether spatial attention could be directed toward an emotional face target while central resources were unavailable. While their behavioral results indicated a PRP effect at short SOA, the N2pc remained indistinguishable across SOA conditions. Thus, visual spatial attention could be deployed toward a target emotion under central load, and this was taken as evidence that emotion perception can occur automatically (Shaw et al., 2011). However, the N2pc is at best an indirect measure of emotion processing. Furthermore, it is possible that the N2pc emotion effect at short SOA was observed because the auditory discrimination task was too easy (Brisson & Jolicoeur, 2007a, 2007b; Lien, Croswaite, & Ruthruff, 2011).

Another PRP effect attributed to a central processing bottleneck is that of backward correspondence, whereby response times to T_1 are faster when the responses for T_1 and T_2 are the same (e.g., positive-positive), compared to when they are not the same (e.g., positive-negative); and the fact that this effect is greater at short versus long SOAs is taken as evidence of automatic processing (Hommel, 1998). One recent PRP study relied on this effect in two experiments to further investigate the question of emotion perception automaticity as a function of age (Allen, Lien, & Jardin, 2017). They had younger and older adults discriminate between positive (happy)/negative (angry) facial expressions (T_1), and discriminate between positive (e.g., laugh)/neutral (e.g., cork pop)/negative (e.g., punch) sounds (T_2). Young adults showed an increased backward correspondence effect for negative stimuli in two experiments, and for positive stimuli in the first experiment. Older adults on the other hand showed an increased backward correspondence effect for positive emotions in the first experiment, and for negative stimuli in the second experiment. Interestingly, saliency and duration of the negative T_2 stimulus was varied between experiments: A short duration punch (low saliency) was used in Experiment 1, and a long duration male scream (high saliency) was used in Experiment 2. Thus, emotion perception might occur without central attention, with a possible mediating effect of emotion valence/saliency, and an age-related arousal/cognitive resources deficit. However, saliency was not manipulated on positive T_2 targets. Valence and saliency are thus confounded.

As is often the case then, the emerging picture is not all-or-none, but instead appears to be drawn in shades of gray; whereby some types of emotional information (e.g., negative or high saliency) might be better suited to automatic processing, and other types of emotional information (e.g., positive or low arousal), less well suited. Drawing upon an extensive psychophysical literature on emotion recognition, we sought to examine if the information conveyed by the visual input could help elucidate what specifically enables/precludes the processing of some facial emotional content under cognitive load. There exists a wealth of evidence showing that not all visual information found in the human face is equally useful for emotion processing. Indeed, some facial regions convey more useful information for emotion recognition, while other facial regions convey information that is less useful for this task (e.g., Blais, Fiset, Roy, Saumure Régimbald, & Gosselin, 2017; Duncan et al., 2017; Smith, Cottrell, Gosselin, & Schyns, 2005; Smith & Merlusca, 2014). Critically, useful (henceforth referred to as "diagnostic") information varies across facial emotions as a function of both low-level image properties (Duncan et al., 2017; Smith et al., 2005), and categorization task (Smith & Merlusca, 2014; see also, for a theoretical overview, Gosselin & Schyns, 2002). An important limitation of the studies presented above (Allen et al., 2017; Shaw et al., 2011; Tomasik et al., 2009) is that low-level image properties (e.g., luminance and spatial frequency), which are processed in early visual cortices (see, for review, De Valois & De Valois, 1990), were not experimentally controlled and might therefore have been confounded for semantic (i.e., emotion) processing (Gosselin & Schyns, 2002). Indeed, the P1 (or P100) visually evoked potential, a well-known electrophysiological index of low-level visual processing (Rossion & Caharel, 2011), can readily discriminate between stimulus categories. It can for example discriminate faces and objects (Rossion & Caharel, 2011), and even emotional and neutral faces, from low-level information alone (Mavratzakis, Herbert, & Walla, 2016); relatedly, behavioral data shows that faces and objects can also be discriminated on low-level information alone (Honey, Kirchner, & VanRullen, 2008). Importantly, equating low-level properties eliminates the between-categories modulation of P1 amplitude (Bekhtereva, Craddock, & Müller, 2015); hence, the importance of controlling for low-level image properties if we are to disentangle low-level from higher-level emotion effects.

Thus, we wondered whether diagnostic information for emotion recognition (which is a product of an interaction between bottom-up and top-down processes) varies as a function of cognitive load using images for which low-level properties were equated (see the Method section). However, central bottleneck procedures might not be sensitive enough to detect all central interference effects on visual processing (e.g., Brisson & Jolicoeur, 2007b; Tombu & Jolicoeur, 2003). Indeed, Brisson and Jolicoeur (2007b) have shown that early visual processing of a T_2 target, as indexed by the occipital N1 evoked potential (approximately 150 to 190 ms at electrodes PO7/PO8) is altered under cognitive load from a demanding auditory T_1; an effect that could not be captured by locus-of-slack procedures.

We were particularly interested in processing of the eye region for several reasons. First, the face sensitive N170 visually evoked potential (Bentin, Allison, Puce, Perez, & McCarthy, 1996), which shares a similar topography and time signature as the N1 (above), was found to be strongly tuned to the diagnostic information of the basic facial expressions (Schyns, Petro, & Smith, 2007), and more specifically, to the eye region (Rousselet, Ince, van Rijsbergen, & Schyns, 2014). The N170 is frequently associated with activity in the fusiform face area (FFA; e.g., Sadeh, Podlipsky, Zhdanov, & Yovel, 2010), a functionally defined region in the fusiform gyrus that exhibits enhanced processing of faces (Kanwisher, McDermott, & Chun, 1997). Crucially, intracranial recordings in this region show that it responds strongly to the eyes (Ghuman et al., 2014), and functional imaging data also shows that face-specialized mechanisms are sensitive to manipulations of visual spatial attention (Wojciulik, Kanwisher, & Driver, 1998). Thus, a cognitive load might alter processing of the eyes in extrastriate cortices.

Second, there is evidence indicating that the amygdala is also responsive to the eyes. Indeed, it was argued, based on clinical evidence, that processing of this feature might be gated by spatial attention—an idea that was put forward to explain the visual strategies of Patient SM and her selective deficit in the recognition of facial expressions of fear (Adolphs et al., 2005). In addition, neuroimaging data has also linked amygdala reactivity with saliency of the eyes (Whalen et al., 2004). As mentioned earlier, the emotional modulation of the amygdala was shown to be altered under cognitive load (e.g., Pessoa et al., 2002; Sebastian et al., 2017). Furthermore, the amygdala and fusiform gyrus are directly connected via the inferior longitudinal fasciculus (Amaral, 2002), allowing the amygdala to influence activity in the fusiform gyrus in response to faces (Herrington, Taylor, Grupe, Curby, & Schultz, 2011), and perhaps especially emotional faces (Vuilleumier et al., 2001). Thus, a possible outcome of cognitive load on the amygdala could also be a reduction in processing of the eyes, either directly or indirectly.

Finally, it is well known that spatial attention can modulate spatial resolution (Yeshurun & Carrasco, 1999), and the eye region of the face stimulus is especially rich in higher spatial frequencies. Seeing how central attention was found to interact with the deployment of spatial attention under difficult auditory T1 conditions (e.g., Brisson & Jolicoeur, 2007a, 2007b), we expected such a central load to selectively interfere with visual processing of the eye region.

To verify this possibility, we used the PRP dual-task paradigm combining a difficult auditory tone categorization task (T_1) and a facial expressions recognition task (T_2) involving the six basic facial emotions (i.e., anger, disgust, fear, happiness, sadness, and surprise; Ekman & Friesen, 1975; Izard, 1971). However, locus-of-slack might not be sensitive enough (Brisson & Jolicoeur, 2007b), and backward correspondence would be impractical for a dual task such as proposed in these pages. Moreover, emotion labeling was shown to be delayed by central load (Phillips, Channon, Tunstall, Hedenstrom, & Lyons, 2008), which (in part) prompted Shaw and colleagues (2011) to employ electrophysiological measures of visual spatial attention. For these reasons, we relied on the psychophysical method of bubbles (Gosselin & Schyns, 2001). Bubbles is a data-driven procedure from the same family as reverse correlation that we chose for its robust and unconstrained image sampling. It has successfully been used to expose how the eyes and mouth are diagnostic of facial emotions in neurologically intact subjects (e.g., Blais et al., 2017; Blais, Roy, Fiset, Arguin, & Gosselin, 2012; Duncan et al., 2017; Smith et al., 2005), and also how failure to process this information can cause severe impairments in the recognition of facial expressions (Adolphs et al., 2005; Fiset et al., 2017). Critically, when used in conjunction with electrophysiological measures, bubbles have revealed that the processing of diagnostic facial emotion information occurs in the N170 window, much earlier than emotion labeling (Schyns et al., 2007). Thus, bubbles should be an appropriate method for investigating the issue at hand; and should it reveal differences in diagnostic information, these should be taken as indicative of an effect of central load on perceptual processes, not emotion labeling.

Method

Participants in the experimental group completed a PRP dual-task in which they first classified the pitch of an auditory stimulus and then categorized "bubblized" facial expressions. Central load was manipulated by varying the SOA. A control version of the task was administered to a second group to eliminate the possibility of perceptual interference; that is, the possibility that hearing a sound (vs. hearing and categorizing a sound) is sufficient to induce the changes that were observed in the experimental group.

Participants

Forty participants (20 per group; 28 females; Aged 18–35) were recruited at the Université du Québec en Outaouais (UQO) and received financial compensation for their participation. All had normal or corrected-to-normal visual acuity. This experiment was approved by the UQO Research Ethics Committee.

The PRP effect size is typically very large and is reliably obtained with small samples (e.g., fewer than 10 participants in Brisson & Jolicoeur, 2007a). An analysis was conducted to achieve a power of 0.8 with an (conservatively) anticipated effect size of $d = .8$, yielding a required sample size of 15 (Faul, Erdfelder, Buchner, & Lang, 2009). Because bubbles require many trials, but also to minimize a possible effect of practice on the psychological refractory period (Van Selst, Ruthruff, & Johnston, 1999), we favored a modestly larger sample.

Apparatus

The experiment was conducted on Apple Mac Mini computers (Intel i7 2.6GHz processor) using custom Matlab (Natick, MA) code and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Auditory stimuli were emitted by headphones. Visual stimuli were displayed on 24-in. BenQ LCD monitors with evenly distributed luminance values and a resolution of 1,920 × 1,080. The refresh rate was 120 Hz. Stimulus average luminance was the same as the gray background (66.3 cd/m^2). Participants sat in a dark room, and a chin rest was used to ensure that they maintained the appropriate viewing distance.

Stimuli

Auditory stimuli were four pure tones: 200 Hz (68 dB), 400 Hz (60 dB), 800 Hz (60 dB), and 1,600 Hz (57 dB). Visual stimuli were 60 grayscale pictures from the Karolinska Directed Emotional Faces (KDEF) database (Lundqvist, Flykt, & Öhman, 1998), downscaled to 256 × 256. Ten identities (five females), depicted the basic facial emotions: anger, disgust, fear, happiness, sadness, and surprise (Ekman & Friesen, 1975; Izard, 1971).

Faces were spatially aligned along the eyes, nose, and mouth, using translation, rotation, and scaling. Spatial frequency spectra and luminance histograms were equalized with SHINE (Willenbockel et al., 2010) to reduce low-level interstimulus variance. An oval that seamlessly blended with the background was applied to faces to hide external features. Face width was 4.3°.

Procedure

Participants in the experimental condition ($N = 20$) were first trained separately in the auditory and visual task. They completed as many blocks ($M = 1.52$; $SD = 0.98$) of 48 trials as needed to achieve 90% correct auditory stimulus categorization; and then completed as many blocks ($M = 4.86$; $SD = 2.17$) of 48 trials as needed to achieve 90% correct facial emotion recognition. Having succeeded these two stages, participants were then trained in the auditory-visual dual task, whereby they completed as many blocks ($M = 4.93$; $SD = 3.16$) of 96 trials as needed to achieve 90% correct categorization with both auditory and visual targets. A trial began with a central fixation point which remained visible throughout—except during visual stimulus presentation. Participants began the trial by pressing the keyboard spacebar, engaging a 500 ms delay after which a pure tone (150 ms) was presented and then, following a SOA of 300 (SOA_{300}) or 1,000 ($SOA_{1,000}$) ms, a face (150 ms) was presented, centered on the monitor. Instructions emphasized quick and accurate responses as targets unfolded. Participants responded to auditory cues by pressing the "a" (low tone; left pinky finger) and "s" (high tone; left ring finger) keyboard keys; and responded to visual cues by pressing the "f" (anger; left middle finger), "g" (sadness; left index finger), "h" (disgust; right index), "j" (fear; right middle), "k" (joy; right ring), and "l" (surprise; right pinky) keyboard keys. During practice blocks, feedback (correct/ incorrect) was provided separately for auditory stimuli (1° above the fixation cross) and visual stimuli (1° below the fixation cross).

The experimental task was identical, except that there was no feedback, and faces were revealed through bubbles (Gosselin & Schyns, 2001), that is, opaque masks punctured by a number of randomly located Gaussian apertures (Figure 1) with a full width at half maximum (FWHM) of 39.96 pixels (0.95° of visual angle). The number of bubbles—and thus, the amount of information revealed—was adjusted on a participant basis with QUEST (Watson & Pelli, 1983) to keep accuracy near 58,33% correct, halfway between ceiling (100%) and floor (16.67%) performance. This is because the data are analyzed by weighting correct against incor-

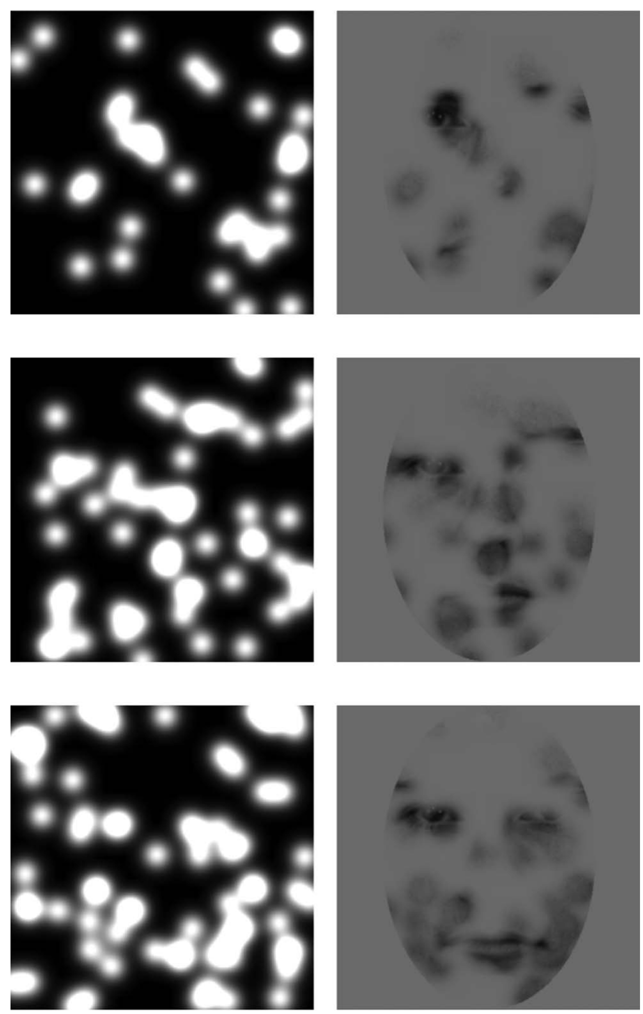

Figure 1. Example of three different bubbles masks, as applied to the same face: 34 bubbles (top), 57 bubbles (middle), and 73 bubbles (bottom). Face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998).

rect responses, and these would convey no information if participants performed at floor/ceiling levels. Participants completed 20 blocks of 96 trials (1,920 total).

Participants in the control group ($N = 20$) were trained on the visual task only ($M = 6.43$ blocks, $SD = 2.48$). They then completed a task identical to the dual task described above, except that they were told to ignore auditory cues and focus exclusively on the categorization of facial expressions.

Classification Image Procedure

Visual strategies were extracted using a classification image procedure (Eckstein & Ahumada, 2002; Gosselin & Schyns, 2004) analogous to a multiple linear regression of bubble coordinates (independent variable) on response accuracies (dependent variable). The logic here is that when bubbles reveal information that match an observer's representation or visual information extraction strategies, the probability of a correct response should increase. If, on the contrary, bubbles reveal information that does not match a representation (or matches an incorrect representation), then the probability of an incorrect response should increase. Hence, the weighted sum of bubbles procedure that was employed, whereby positive weights were allocated to bubbles masks presented on correct trials, and negative weights were allocated to bubbles masks presented on incorrect trials. The weights in question were the accuracy scores (*correct* = 1; *incorrect* = 0) from the appropriate subset of trials—angry trials for anger, and so forth—which were transformed into *z* scores, using the mean and standard deviation of accuracies from the same subset of trials. The standardization of accuracies was done so that equal weight was given to correct (of which there were more) and incorrect (of which there were fewer) responses.

For combined expressions, bubbles data were analyzed with the experiment FWHM value (equal to 0.95°). The outcome was a series of n (sample size = 20) $\times$ e (emotion conditions = 6) $\times$ s (SOA conditions = 2) matrices (i.e., classification images) of coefficients quantifying the association between a given pixel and accurate facial expression recognition. These were standardized (transformed into *z* scores) with the mean and standard deviation of the null hypothesis, the parameters of which were estimated with pixels from the signal-less background (Chauvin, Worsley, Schyns, Arguin, & Gosselin, 2005). Group classification images for each SOA condition were then created by summing individual classification images across subjects and across emotions, and within SOA. The outcome was then divided by $\sqrt{ne}$.[1]

The two-tailed statistical thresholds were determined with a pixel ($Z_{\text{critP}} = 3.617$, $p < .05$) and cluster ($Z_{\text{critC}} = 2.3$, $k = 1{,}535$ pixels, $p < .05$) test for a FWHM value of 0.95°, with the former intended for isolated pixels with high *z* score values, and the latter intended for wider regions of contiguous pixels with relatively lower *z* score values (Chauvin et al., 2005). Importantly, both tests apply a correction for multiple observations, but also account for the nonindependence of contiguous pixels, determined by the bubble smoothing factor (i.e., FWHM).

For individual expressions, we analyzed bubbles data with a doubled FWHM value (1.9°) to compensate for the resulting decrease in power (for an argument on why this is an appropriate procedure, the reader is referred to Chauvin et al., 2005). Individual classification images were standardized using the permutation procedure outlined above, and group classification images were created by summing individual classification images across subjects, within emotion and within SOA condition. The outcome was divided by $\sqrt{n}$.

Analyses and Results

Experimental Group

Auditory task. Average accuracy was 90.8% correct (95% CI [88.4%, 93.2%]; $SD = 5.2\%$) at SOA_{300}, and 91.6% correct (95% CI [89.6%, 93.6%]; $SD = 4.3\%$) at $\text{SOA}_{1,000}$; the difference was marginally significant, $t(19) = 2.04$, $p = .06$, $d = .458$. Response times were 1,594.5 ms (95% CI [1,355.8, 1,833.3], $SD = 510.1$ ms) at SOA_{300}, and 1,750.6 ms (95% CI [1,507.7, 1,993.5], $SD = 519.1$ ms) at $\text{SOA}_{1,000}$, and the difference between the two conditions is significant, $t(19) = 3.51$, $p = .002$, $d = .786$. To test for response grouping (i.e., when participants postpone their response to T_1 until they are ready to also answer T_2), inter response intervals (IRI) in the SOA_{300} condition were calculated with the equation IRI = RT2 + 300 – RT1 on an individual subject and trial basis. Response grouping was defined as IRIs smaller than 150 ms on more than one third of trials (as per Allen et al., 2017). Three subjects were found to group their responses in the SOA_{300} condition, but Pashler and Johnston (1989) showed that response grouping should not affect T_2 results. We nonetheless carried subsequent analyses, including and excluding these three subjects; seeing as this did not alter the outcome, we chose to include their data in the report.

Though the other subjects did not group their responses, IRIs were still noticeably shorter in the SOA_{300} condition ($M = 945$ ms, $SD = 334$ ms), compared to the $\text{SOA}_{1,000}$ condition ($M = 1{,}292$ ms, $SD = 431$ ms), $t(16) = 8.57$, $p < .001$, $d = 2.08$. Thus, it appears that T_2 onset might have precipitated T_1 response output in the SOA_{300} condition, which could have resulted in a slight speed-accuracy tradeoff that may explain the marginal reduction in T_1 accuracy at SOA_{300}.

Visual task.

Performance. Only trials with accurate auditory task responses ($M = 1{,}752$ trials; 95% CI [1,709, 1,793]; $SD = 90$) were analyzed. On average, 49 bubbles (95% CI [38, 61]; $SD = 24$) were needed to maintain an accuracy of 64.54%, approximately 6% higher than the targeted (58.33%) performance. This discrepancy between targeted/achieved performance is not unusual, nor is it too large to be problematic. The key goal of this procedure is merely to avoid that participants hit floor/ceiling performances, which would void the analysis of bubbles data, and as evidenced below, this objective was achieved.

We conducted a 6 (emotion: anger, disgust, fear, happiness, sadness, and surprise) $\times$ 2 (SOA: 300 ms, 1,000 ms) repeated measures analysis of variance (ANOVA) on correct responses. Unsurprisingly, there was a significant emotion effect, $F(5, 95) = 54.83$, $p < .001$, $\eta_p^2 = 0.74$, reflecting the fact that some expres-

[1] Since the standard deviation of the sum of normally distributed observations (here, the group classification image) is equal to the square-root of the sum of their variances, $\sigma_{\text{sum}} = \sqrt{\sigma_1^2 + \ldots \sigma_{ne}^2}$, then it follows that $\sigma_{\text{sum}} = [\sqrt{\sigma_1^2} + \ldots \sqrt{\sigma_{ne}^2}]/\sqrt{ne} = [\sigma_1 + \ldots \sigma_{ne}]/\sqrt{ne}$.

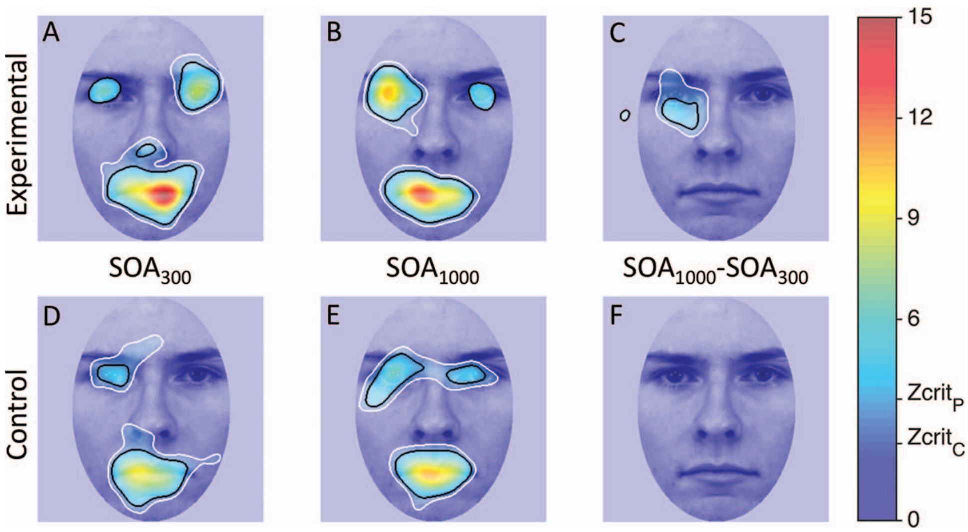

Figure 2. Classification images for the experimental (top) and control (bottom) conditions, at SOA_{300} (left), $\text{SOA}_{1,000}$ (middle), and also for the $\text{SOA}_{1,000}$-SOA_{300} difference (right). Regions outlined with a white line are significant at the cluster level, $Z_{\text{critC}} = 2.3$, $k = 1{,}535$ contiguous pixels, $p = .025$ (corrected for multiple comparisons). Regions outlined with a black line are significant at the pixel level, $Z_{\text{critP}} = 3.617$, $p = .025$ (corrected for multiple comparisons). A color version of this figure is available in the online version of the article. Face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998). See the online article for the color version of this figure.

sions are more difficult to recognize than others ($M_{\text{anger}} = 60.8\%$, $SD = 8.5\%$; $M_{\text{disgust}} = 59.4\%$, $SD = 10.2\%$; $M_{\text{fear}} = 56.1\%$, $SD = 8.5\%$; $M_{\text{happiness}} = 90.2\%$, $SD = 6.7\%$; $M_{\text{sadness}} = 65.5\%$, $SD = 6.7\%$; $M_{\text{surprise}} = 55.3\%$, $SD = 11.1\%$). There was no SOA effect, $F(1, 19) = 0.003$, $p > .9$, $\eta_p^2 = 0$, as performance was similar at SOA_{300} ($M = 64.55\%$ correct; 95% CI [62.21, 66.89]; $SD = 5\%$) and at $\text{SOA}_{1,000}$ ($M = 64.52\%$ correct; 95% CI [61.91, 67.13]; $SD = 5.58\%$). There was also no Emotion × SOA interaction, $F(5, 95) = 0.454$, $p > .7$, $\eta_p^2 = 0.023$.

We conducted the same 6 (emotion) × 2 (SOA) repeated measures ANOVA, this time on response times. Again, there was a significant emotion effect, $F(2.963, 56.3) = 30.98$,[2] $p < .001$, $\eta_p^2 = 0.62$, once more reflecting the fact that some expressions are more difficult (require more processing time) to recognize than others ($M_{\text{anger}} = 1{,}701$ ms, $SD = 429$ ms; $M_{\text{disgust}} = 1{,}671$ ms, $SD = 434$ ms; $M_{\text{fear}} = 2{,}014$ ms, $SD = 649$ ms; $M_{\text{happiness}} = 1{,}265$ ms, $SD = 340$ ms; $M_{\text{sadness}} = 1{,}768$ ms, 555 ms; $M_{\text{surprise}} = 1{,}664$ ms, 510 ms). There also was the expected SOA effect, $F(1, 19) = 87.31$, $p < .001$, $\eta_p^2 = 0.82$, meaning that emotion recognition took 250.6 ms longer at shorter SOAs, as average response times were 1,797 ms (95% CI = [1,567.9, 2,026]; $SD = 489.3$ ms) at SOA_{300}, and 1,546.4 ms (95% CI [1,343.2, 1,749.7], $SD = 434.2$ ms) at $\text{SOA}_{1,000}$. This PRP effect indicates that there was central interference at some processing stage in this task. Finally, there was a marginal Emotion × SOA interaction effect, $F(5, 95) = 2.25$, $p = .06$, $\eta_p^2 = 0.11$. Paired-samples t tests (uncorrected) revealed that there was a significant PRP effect for all expressions, but the size of this effect varied across emotions ($M_{\text{anger}} = 307$ ms, [$SD = 226$ ms]; $M_{\text{disgust}} = 242$ ms, $SD = 165$ ms; $M_{\text{fear}} = 219$ ms, $SD = 219$ ms; $M_{\text{happy}} = 232$ ms, $SD = 184$ ms; $M_{\text{sadness}} = 181$ ms, $SD = 155$ ms; $M_{\text{surprise}} = 328$ ms, $SD = 195$ ms), all ts$(19) > 4.47$, all ps $< .001$.

Bubbles data. To examine whether visual information utilization was affected by central interference, we extracted diagnostic information for combined expressions for each SOA condition. Figure 2 illustrates diagnostic information for the experimental SOA_{300} (Figure 2A) and $\text{SOA}_{1,000}$ (Figure 2B) conditions. As illustrated, the eyes and mouth significantly positively correlated with emotion categorization accuracy at SOA_{300} ($Z_{\max} = 11.87$) and SOA_{1000} ($Z_{\max} = 10.13$), both ps $<.001$. However, subtracting SOA_{300} from SOA_{1000} reveals an SOA effect that manifests as a reduction in reliance on the left eye ($Z_{\max} = 4.2$; Figure 2C), $p < .001$. To verify that this result was not due to a small subset of participants, we averaged individual regression coefficients (z scores) that fell within the left eye region (see darkened region on the right-hand side image of Figure 3) at SOA_{300} ($M = .463$; 95% CI [.091, .836]; $SD = .795$) and $\text{SOA}_{1,000}$ ($M = 1.231$; 95% CI [.926, 1.536]; $SD = .651$) and submitted these to a paired-samples t test. The difference ($M = .768$; 95% CI [.281, 1.254]; $SD = 1.039$) remained significant, $t(19) = 3.304$, $p < .005$, $d = .74$.

To examine this SOA effect on an emotion basis we averaged the regression coefficients (z scores) that fell within the left eye region, for each emotion and SOA combination. We then conducted a 6 (Emotion) × 2 (SOA) repeated measures ANOVA on left eye utilization. Unsurprisingly, there was a significant main effect of emotion, $F(3.25, 61.74) = 4.19$, $p < .01$, $\eta_p^2 = 0.18$, reflecting that left eye utilization differs across emotions ($M_{\text{anger}} = 0.98$, $SD = 0.13$; $M_{\text{disgust}} = 0.09$, $SD = 0.11$; $M_{\text{fear}} = 0.46$, $SD = 0.16$; $M_{\text{happiness}} = 0.06$, $SD = 0.17$; $M_{\text{sadness}} = 0.32$, $SD = 0.14$;

[2] Throughout this text, Greenhouse-Geyser corrections are applied when sphericity assumptions are violated.

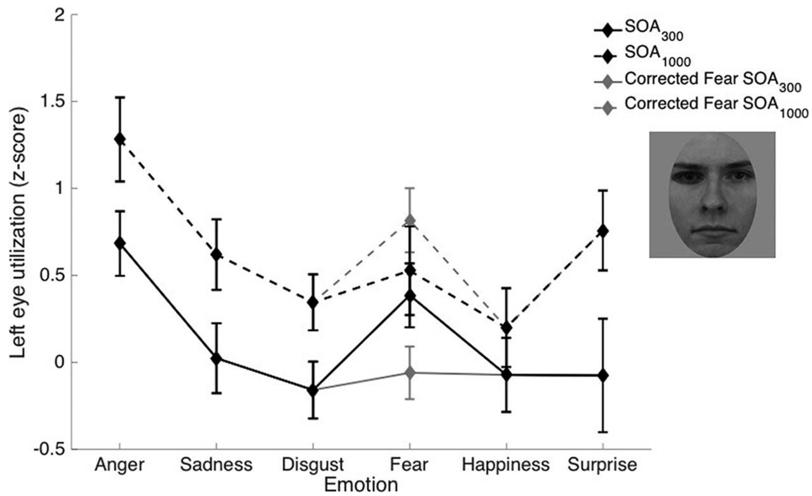

Figure 3. Graph plotting the experimental group average utilization of the left eye region (darkened pixels) across the SOA_{300} (black, continuous line) and SOA_{1000} (black, dotted line) conditions for individual facial expressions, along with the standard error of the mean. Results for the corrected classification image of fear are indicated in gray. Face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998).

$M_{\text{surprise}} = 0.34$, $SD = 0.24$). Importantly, there was a significant main effect of SOA, $F(1, 19) = 23.944$, $p < .001$, $\eta_p^2 = 0.56$, with average eye utilization smaller at SOA_{300} ($M = 0.13$, $SD = 0.09$) compared to $SOA_{1,000}$ ($M = 0.622$, $SD = 0.08$), but no SOA × Emotion interaction, $F(5, 95) = 0.68$, $p > .6$, $\eta_p^2 = 0.03$. Thus, the decrease in left eye utilization at SOA_{300} versus $SOA_{1,000}$ was generalized across emotions (see also Figure 3).

Given that the recognition of fear is strongly dependent on the eyes (e.g., Adolphs et al., 2005; Smith et al., 2005), and that this emotion is often associated with automatic emotion processing (e.g., Vuilleumier et al., 2001), we wished to further explore this specific emotion. Indeed, despite the fact that there was no statistical Emotion × SOA interaction, the effect of SOA on fear ($d = 0.1$) was the least pronounced (see Figure 3), which might suggest some degree of automatic processing of the left eye for this emotion. However, looking at response patterns revealed an overall increased disposition toward responding "fear." Indeed, though this expression was presented on 16.67% of trials, fear responses were given on 19% of trials, and this was previously shown to distort the classification image (Duncan et al., 2017). Thus, we reanalyzed fear-present trials to remove from correct fear responses the variance explained by the overall greater disposition to respond fear (see, for a similar procedure and rationale, Duncan et al., 2017). Specifically, a corrected classification image for fear was created using the procedure outlined in the Method section, using instead hits (fear responses on fear-present trials) and false alarms (fear responses on other-present trials) as weights for bubbles masks. Left eye utilization at SOA_{300} ($M = -0.06$; $SD = 0.68$) and $SOA_{1,000}$ ($M = 0.82$; $SD = 0.82$) was then compared with a paired-samples t test and found to be significantly different, $t(19) = 3.63$, $p < .005$, $d = 0.8$.

Interestingly, we noticed what appears to have been a lateralization shift induced by the change in SOA. This is supported in two empirical ways. First, the classification image centroids (i.e., highest regression coefficients [z scores]) for the eyes and mouth are, respectively, located at 80% and 58.9% face width at SOA_{300}, and at 21.7% and 43.3% face width at SOA_{1000} (with values <50% corresponding to the left face half, and values >50% corresponding to the right half). Second, the distribution of all significant pixels (including those of the eyes and mouth) follows the same shift. As illustrated in Figure 4 (solid black line), there are more significant pixels on the right side of the face at SOA_{300}, and more significant pixels on the left side of the face at $SOA_{1,000}$. A bootstrap analysis consisting of 1,000 Monte Carlo simula-

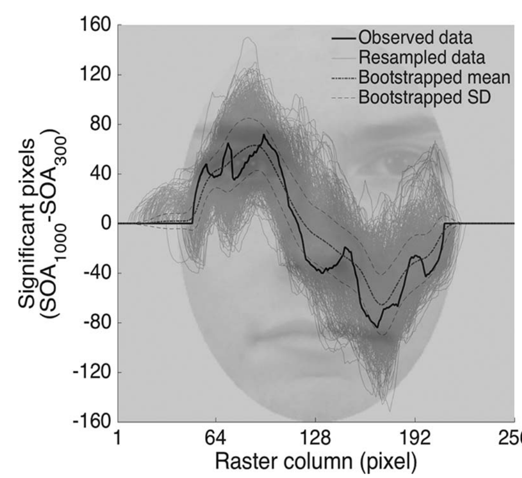

Figure 4. Difference in the distribution of significant pixels across face width at SOA_{300} and at $SOA_{1,000}$. Positive values indicate that there are more significant pixels at $SOA_{1,000}$, and negative values indicate that there are more significant pixels at SOA_{300}. The solid black line plots the observed data. The solid gray lines plot each of the 1,000 individual Monte Carlo simulations. The dash-dotted and dashed gray lines, respectively, plot the bootstrapped estimate of the mean and standard deviation of the $SOA_{1,000}$-SOA_{300} difference in significant pixels. Background face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998).

tions—resamples of size $n = 20$, with replacement—shows that this effect is highly reliable (see Figure 4, solid gray lines). Indeed, a right-side bias in the SOA_{300} condition emerged in 99.6% of simulations with an FWHM of 20.7% face width (measured on the bootstrapped mean; Figure 4, dash-dotted line), whereas a left-side bias in the $SOA_{1,000}$ condition was observed in 100% of simulations with an FWHM of 27.4% face width.

Control Group

Performance. In the control condition, all 1,920 trials were analyzed. Participants needed an average of 60.16 bubbles ($SD = 16.74$) to maintain 64.77% correct responses. This number of bubbles is marginally greater than that required by participants in the experimental condition, $t(38) = 1.65$, $p = .11$, $d = 0.52$, indicating that participants in the experimental condition tended to do better in the visual task despite the same performance criterion being applied during the learning phase, and thus, that the two groups were perhaps not an exact match as it pertains to ability levels. Indeed, control group participants needed an average of 1.57 more practice blocks to achieve the performance criterion, compared to the experimental group, $t(38) = 2.18$, $p < .05$. Furthermore, participants from the experimental group benefited from additional practice because they were trained twice with facial expressions—once in a single task setting, and once in a dual task setting; whereas participants in the control group were trained once in single task only.

Interestingly, the control group average response times in the visual task at SOA_{300} were 1,311 ms (95% CI [1,223, 1,400], $SD = 189$), and 1,349 ms (95% CI [1,258, 1,440], $SD = 195$) at $SOA_{1,000}$; thus, contrary to the experimental group, there was a small but significant 38 ms increase in response times at $SOA_{1,000}$, $t(19) = 4.209$, $p < .001$, $d = .94$. The auditory perception of tones therefore cannot, by itself, explain the PRP effect on response times that was observed in the experimental group. Instead, it is possible that the proximity between auditory tones and visual stimuli in the SOA_{300} condition, in the absence of a need to categorize auditory tones, had the effect of increasing preparedness to carry the visual task, resulting in a modest speed-accuracy tradeoff. Furthermore, when compared to the experimental group, the control group response times were on average 486 ms ($SD = 375$ ms) faster in the SOA_{300} condition, $t(38) = 4.1$, $p < .001$, $d = 1.3$; and 197 ms ($SD = 339$ ms) faster in the $SOA_{1,000}$ condition, $t(38) = 1.84$, $p = .07$, $d = 0.58$. Thus, it is possible that participants in the control group performed marginally worse because they were objectively worse, because they completed fewer practice blocks overall, and also because they responded faster compared to participants in the experimental group and thus committed more errors as a result of a speed-accuracy tradeoff.

Bubbles data. Despite this apparent difference in performance, information utilization was generally similar across both groups and conditions. Indeed, as was the case for the experimental group, the eyes and mouth significantly (FWHM = 0.95, $Z_{crit} = 3.67$, $p < .025$) positively correlated with emotion categorization accuracy at SOA_{300} ($Z_{max} = 8.59$) and SOA_{1000} ($Z_{max} = 9.57$), both ps <0.001. Figure 2 (D and E) shows the information that was used across facial expressions by participants in the control SOA_{300} (Figure 2D) and $SOA_{1,000}$ (Figure 2E) conditions. Critically, subtracting SOA_{300} from $SOA_{1,000}$ (Figure 2F) reveals that there was no SOA effect on utilization of the different facial regions, $Z_{max} = 3.19$, $p > .15$.

To verify that both groups were comparable in terms of overall (i.e., across SOA conditions) utilization of the left eye for individual emotions (FWHM = 1.9°), we conducted a repeated measures ANOVA with emotion (anger, disgust, fear, happiness, sadness, and surprise) as the within-subjects factor, and group (experimental, control) as the between-subjects factor. There was an emotion effect, reflecting differential eyes utilization across emotions, $F(5, 390) = 10.6$, $p < .001$, $\eta_p^2 = 0.12$. Critically, there was no group effect, $F(1, 78) = 1.65$, $p > .2$, $\eta_p^2 = 0.02$, or Emotion × Group interaction, $F(5, 390) = 0.55$, $p > .7$, $\eta_p^2 = 0.01$. Thus, utilization of the left eye was similar in both groups of subjects for all expressions (Figure 5).

As above, we also conducted a 6 (emotion) × 2 (SOA) repeated measures ANOVA on left eye utilization, this time for the control group. Like in the experimental group, there was a significant emotion effect, $F(5, 95) = 7.44$, $p < .001$, $\eta_p^2 = 0.28$, reflecting the fact that left eye utilization differs across emotion conditions ($M_{anger} = 0.74$, $SD = 0.09$; $M_{disgust} = -0.13$, $SD = 0.13$; $M_{fear} = 0.37$, $SD = 0.12$; $M_{happiness} = -0.07$, $SD = 0.14$; $M_{sadness} = 0.18$, $SD = 0.12$; $M_{surprise} = 0.51$, $SD = 0.13$). Critically however, there was no SOA effect, $F(1, 19) = 1.1$, $p > .3$, $\eta_p^2 = 0.06$, as left eye utilization was similar across SOA_{300} ($M = 0.21$; 95% CI [0.05, 0.37]; $SD = 0.89$) and $SOA_{1,000}$ ($M = 0.32$; 95% CI [0.18, 0.46]; $SD = 0.78$) conditions; nor was there an Emotion × SOA interaction effect on left eye utilization, $F(3.64, 69.08) = 1.32$, $p > .25$, $\eta_p^2 = 0.07$ (Figure 6).

Discussion

We hypothesized that central load would selectively interfere with visual processing of the eye region and verified this using the bubbles reverse correlation technique. This hypothesis was partially validated by our results showing central interference on processing of the left eye, but not the right eye. Importantly, this effect was not observed in the control group, despite an increase in statistical power conferred by an additional 9.59% analyzed trials. Furthermore, the results of exploratory analyses also indicate that this effect on left eye utilization might be accompanied by a more generalized decrease in utilization of the left half of the face under cognitive load, and an increase in utilization of the right half. Importantly, this last analysis included all significant pixels (i.e., those from the eye and mouth region); thus, though the eyes will certainly have contributed to this lateralization effect, they are hardly the only face region driving this shift, as there were, in fact, more significant pixels in the mouth region than in the eye region, and the dispersion of mouth centroids (i.e., largest regression coefficients) showed the same lateralization effect.

To explain these effects, we first consider the central point that participants were instructed to fixate. First, its location (relative to the face stimulus) was found to be near-optimal for facial expression perception (Peterson & Eckstein, 2012), and participants were told to refrain from moving their eyes or blinking during the entire stimulus presentation sequence. As a consequence, the mouth and eye regions were most likely projected outside the foveola (i.e., the region with the greatest spatial resolution), and a role for spatial attention is therefore implied. As previously mentioned, the diffi-

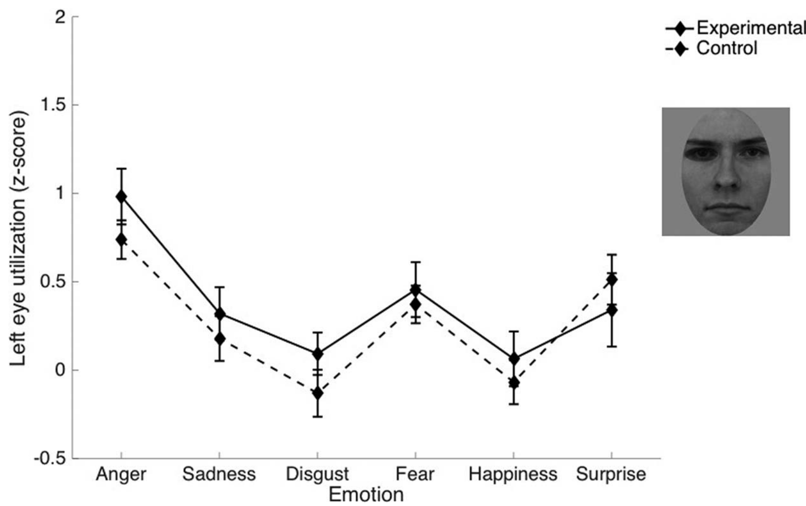

Figure 5. Graph plotting the average utilization of the left eye region (darkened pixels) for the experimental group (continuous line) and the control group (dotted line) across individual facial expressions, along with the standard error of the mean. Face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998).

cult auditory T_1 that we administered was shown to interfere with the deployment of visual spatial attention.

However, very recent work suggests that spatial attention mechanisms in the two cerebral hemispheres might be differentially susceptible to central load (Naert, Bonato, & Fias, 2018). In this study, the researchers parametrically varied central load by having participants hold two or six items in working memory while they performed a basic dot detection task in the left/right visual hemifield (right/left hemispheres, respectively). Although there was a dose-dependent decrement to performance in both hemispheres, this effect was more pronounced in the left hemifield (right hemisphere). The authors proposed that this reflects a right hemisphere disadvantage (RHD) with regard to central load, but also acknowledged the alternate account of left hemisphere advantage (LHA; Kinsbourne, 1970a, 1970b). The lateralization shift (i.e., more significant pixels in the left face half at $SOA_{1,000}$, and more significant pixels in the right face half at SOA_{300}) that we observed indicates that both RHD and LHA may in fact be observed under cognitive load.

In conjunction with the RHD/LHA, cerebral asymmetries with regard to face processing and spatial frequency processing may further explain the more specific decrease in left eye utilization that we observed under cognitive load. We first consider the latter, namely, that the right hemisphere is tuned to relatively lower spatial frequencies, compared to the left hemisphere (see, for review, Robertson & Ivry, 2000). The implication is that, com-

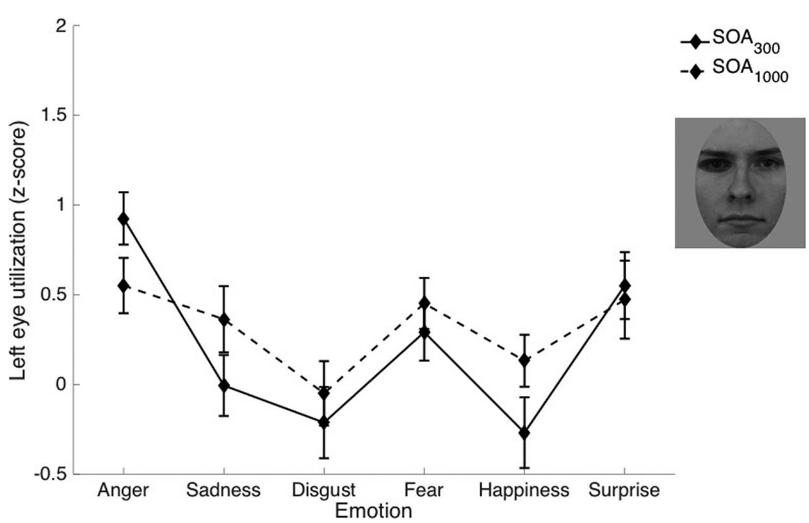

Figure 6. Graph plotting the control group average utilization of the left eye region (darkened pixels) across the SOA_{300} (continuous line) and $SOA_{1,000}$ (dotted line) conditions for individual facial expressions, along with the standard error of the mean. Right-hand side face image taken with permission from KDEF (BM14NES; Lundqvist et al., 1998).

pared to the left cerebral hemisphere, the right hemisphere might require more cognitive resources or rely to a greater extent on spatial attention resolution enhancement (Yeshurun & Carrasco, 1999) in order to efficiently process the higher spatial frequency content found in the eyes. Seeing as spatial attention deployment can be precluded by sufficient central load (Brisson & Jolicoeur, 2007a), our task could have selectively interfered with right hemisphere processing (Naert et al., 2018) of higher spatial frequencies, and as a consequence, also interfered with the processing of the left eye in the right hemisphere (Rousselet et al., 2014; Vinette, Gosselin, & Schyns, 2004).

In addition to spatial frequency tuning, there also exists a cerebral asymmetry with regard to face processing. Indeed, right hemisphere dominance is often found for face processing among right-handed people. For example, acquired prosopagnosia most frequently results from right hemisphere lesions (see, for review, Mayer & Rossion, 2007). In addition, the FFA typically has a greater volume (Kanwisher et al., 1997), and the N170 visually evoked potential has a greater amplitude (Bentin et al., 1996), in the right hemisphere. The FFA is an important region for its purported role in general aspects of face processing, and for our purpose more specifically, because it is also proposed to play a substantial role in the processing of facial expressions (see, for review, Duchaine & Yovel, 2015). Interestingly, results from intracranial electrodes suggest that FFA activity is best predicted by the eye region (Ghuman et al., 2014); and its electrophysiological correlate, the N170 (Sadeh et al., 2010), has been shown to be selectively tuned to information from the contralateral eye, that is, the right hemisphere N170 response is tuned to the left eye, and vice versa (Rousselet et al., 2014). Relatedly, a left eye bias is also typically observed in face identification (Caldara et al., 2005; Gosselin & Schyns, 2002; Vinette et al., 2004) and perhaps also in emotion recognition (Blais et al., 2012; Duncan et al., 2017), and this bias may be attributed to right hemisphere dominance in face processing. Critically, previous research has shown that FFA face selectivity is gated by spatial attention (Wojciulik, Kanwisher, & Driver, 1998; see also Pessoa et al., 2002; Vuilleumier et al., 2001). Thus, the central load that was induced by our task could also have interfered with visual processing in the attention-sensitive face-specialized regions of the right hemisphere, and as a consequence, also selectively interfered with processing of the left eye.

In addition, the amygdala, which has extensively been studied for its role in emotion perception (e.g., Vuilleumier et al., 2001), has also been linked with the eyes (specifically, their saliency; Whalen et al., 2004). This proves especially relevant when we consider the functional link between the amygdala and fusiform gyrus (Herrington et al., 2011), and a recent study showing that the emotional modulation of activity in the right amygdala is greatly reduced under cognitive load (Sebastian et al., 2017). Thus, it is possible that central load interfered with utilization of the left eye; directly (by a reduction of right amygdala reactivity), or indirectly (through amygdala-fusiform functional connectivity).

As for how the present results fit with previous findings, ours point toward a possible mechanism that could explain the relative heterogeneity of findings. It was proposed that valence/saliency could be a mediator of automatic processing (Allen et al., 2017). Though we did not control for saliency, our results on an expression basis for angry, fearful and happy expressions (i.e., emotions frequently used to assess automaticity) appear inconsistent with the prediction of valence. First, the PRP effect on response times was smaller for happy versus angry expressions. And although the PRP effect for fearful expressions was similar to happy expressions, this might simply reflect the fact that response times were overall considerably longer for the former, compared to the latter. Second, the effect of SOA was larger for angry and (corrected) fearful expressions, compared to happy expressions.

A possible explanation for such a discrepancy could be eye/mouth diagnosticity in our respective tasks. As previously mentioned, diagnostic information varies as a function of the type of categorization task. Importantly, in tasks where there were only one or two expression alternatives, the eyes/mouth were found to be much less/more diagnostic of fear, respectively, when happiness was an alternative versus when there were several other alternatives (i.e., the other basic emotions; Smith & Merlusca, 2014). Given the importance of the eye region for angry expressions (Duncan et al., 2017; Smith et al., 2005), a similar effect could be expected for the categorization of this expression. And whereas the current study relied on a task where the six basic emotions were a possible alternative, prior studies relied on tasks discriminating between angry and happy expressions (Allen et al., 2017; Shaw et al., 2011). Thus, the discrepancy in results could reflect differences in diagnosticity of the eye region (which was likely greater in the present study) and diagnosticity of the mouth region (which was likely greater in the studies of Allen et al., 2017 and Shaw et al., 2011).

In conclusion, we have shown a way in which central load appears to interfere with the processing of facial emotions. Specifically, we found a reduction in utilization of the left eye under cognitive load, suggesting that processing of this information, specifically, is not automatic. On the contrary, there was no central interference on processing of the mouth, suggesting that this information may, in fact, be processed automatically. Seeing as the usefulness of the eyes and mouth regions varies across emotions, this might help explain why some emotions appear to be processed automatically and others not. In addition, there also appears to have been a commensurate increase in processing of the right half of the face under central load. Thus, the left cerebral hemisphere might be more resilient to central interference and allow the visual system to cope with the effects of sparseness of central processing resources on the right hemisphere (Naert et al., 2018). This could explain why we found no effect of central load on recognition performance, despite the reduction in utilization of the left eye.

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