Finding patterns in emotional information: Enhanced sensitivity to statistical regularities within negative information

Jonas Everaert[1] *, Ernst H.W. Koster[1], & Jutta Joormann[2]

[1] Ghent University, Belgium

[2] Yale University, United States of America

*** Corresponding author**: Jonas Everaert, PhD.

Ghent University, Department of Experimental Clinical and Health Psychology, Henri Dunantlaan 2, 9000 Ghent, Belgium. E-mail: jonas.everaert@gmail.com

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Abstract

In everyday life, people are exposed to continuous flows of emotional information. The ability to organize and segment this continuous input seems critical to understand what is happening around us. This study investigated whether people are sensitive to subtle statistical regularities embedded in flows of emotional information. Experiment 1 showed that people were able to identify regularities in streams of negative visual scenes. Experiment 2 demonstrated that the ability to extract statistical regularities was enhanced for negative compared to neutral visual scenes. Finally, Experiment 3 found that learning of statistical regularities was similar for negative and positive visual scenes. Across these experiments, we found that explicit awareness of regularities did not modulate statistical learning ability. The results of this study help to understand the processes that enable people to make inferences about the complex input of the emotional world.

Keywords: statistical learning, associative learning, emotional information-processing, visual attention, recognition memory.

Introduction

Many situations in our day-to-day lives are highly structured. For example, traffic lights alternate the right-of-way accorded to users by displaying sequences of standard colors, songs mostly follow a similar structure of alternating strophes and a refrain, and many social interactions involve people displaying sequences of behaviors to start, maintain, and exit a conversation. As these examples imply, the ability to detect such ‘regularities’ or repeated patterns in daily life situations is critical to understanding what is happening around us. Importantly, even though we may not be aware of these regularities, they may still guide our behavior. The process through which people extract probabilistic relationships among stimuli or events that occur in the environment over space or time is referred to as *statistical learning*.

Research on statistical learning has demonstrated that people are sensitive to regularities in continuous flows of information in different sensory modalities and feature dimensions (for reviews, see Frost, Armstrong, Siegelman, & Christiansen, 2015; Krogh, Vlach, & Johnson, 2013; Santolin & Saffran, 2018; Siegelman, Bogaerts, & Frost, 2017). For example, studies have documented that people can detect regularities in sequences of syllables (Saffran, Aslin, & Newport, 1996), actions (Baldwin, Andersson, Saffran, & Meyer, 2008), tones (Creel, Newport, & Aslin, 2004), colors (Turk-Browne, Isola, Scholl, & Treat, 2008), shapes (Fiser & Aslin, 2002), and tactile sensations (Conway & Christiansen, 2005). In a variant of a statistical learning task with real-world visual scenes (Brady & Oliva, 2008), participants were exposed to a continuous stream of images that consisted of four pseudo-randomly repeating triplets (i.e., combinations of three images that always appear in the same order). Critically, participants were not informed about the presence of the triplets and performed a distracting cover task. After viewing the stream of images, participants completed a recognition task in which they were asked to discriminate the triplets from the exposure phase from foil sequences generated from the sample stimuli but rearranged into new groupings. Results showed that participants were able to identify the triplets as more familiar than the foil sequences (Brady & Oliva, 2008). This suggests that participants learned the co-occurrences of the images within the triplets. Interestingly, studies frequently found that individuals are able to discriminate triplets from foil sequences even when they are not aware of any statistical structures (Brady & Oliva, 2008; Fiser & Aslin, 2002; Turk-Browne, Jungé, & Scholl, 2005; Zhao, Al-Aidroos, & Turk-Browne, 2013). Investigators have then argued that statistical learning involves a form of learning that does not require intent or explicit awareness (Kim, Seitz, Feenstra, & Shams, 2009; Turk-Browne et al., 2005).

Despite a myriad of studies on statistical learning, currently little is known about the ability of human subjects to extract statistical regularities embedded in continuous flows of *emotional* information. Indeed, prior research on statistical learning has focused on emotionally neutral information, but it has not examined whether people are sensitive for repeated patterns in emotional stimuli. Yet, statistical learning of regularities in flows of emotional information seems particularly important for psychological adaptation given that many aspects of our emotional lives co-occur. For example, co-varying physical, behavioral, and emotional responses of increased muscle tension, clenched fists, and hostility may warn you when someone will burst out in anger. Detecting patterns in co-occurring facial and vocal expressions (e.g., eyebrows drawn in and up, corners of the lips turned down, speech characterized by a large proportion of pauses and decreases in precision of articulation, etc.) may help you to recognize specific emotions (e.g., sadness) and express empathy in conversations with your partner. The ability to detect the covariance between emotional cues may allow people to uncover structures in complex emotional input, make predictions about emotional situations, and respond to those situations adequately. Indeed, it has long been known that people acquire information about relations between simple stimulus – outcome (e.g., reward, punishment) pairs through associative learning (Bourgeois, Chelazzi, & Vuilleumier, 2016; Le Pelley, Mitchell, Beesley, George, & Wills, 2016). Yet, an unexplored question is whether people can organize and segment continuous flows of emotional information to extract more complex regularities with the goal of predicting the emotional world.

Both emotional information and statistical regularities are considered important sources of salience that attract attention (Todd & Manaligod, 2017). However, emotional stimuli may influence statistical learning in various ways when they compete for prioritization. It is plausible that emotional stimuli *enhance* learning of statistical regularities. Research has repeatedly shown that emotional information is prioritized over neutral information in cognitive processes such as attention and memory (Mather & Sutherland, 2011; Todd, Cunningham, Anderson, & Thompson, 2012; Vuilleumier & Huang, 2009). For example, studies on emotional attention have demonstrated that both positive and negative stimuli are detected faster than neutral stimuli (Pool, Brosch, Delplanque, & Sander, 2015; Yiend, 2010). Likewise, studies on emotional memory have shown that negative and positive stimuli are better remembered than neutral stimuli (Hamann, 2001; Talmi, 2013). Thus, the emotional salience of stimuli may mobilize processing resources and bias information processing so that it facilitates the detection of regularities in streams of emotional information. This may then enhance learning of statistical regularities that occur in emotional relative to neutral information.

By contrast, it is possible that emotional stimuli *impair* statistical learning for emotional information. Research has frequently documented that emotionally arousing stimuli may interfere with cognitive processes (Dolcos, Wang, & Mather, 2014; Mather & Sutherland, 2011). For instance, studies have found that emotional stimuli may reduce working memory capacity compared to neutral stimuli (Garrison & Schmeichel, 2018; Schweizer & Dalgleish, 2016). Furthermore, research has shown that memory for locations of different images is worse when the images shown during a source-monitoring task depicted emotional compared to neutral stimuli (Mather et al., 2006). In explaining such impairing effects by emotion, researchers have proposed that emotional arousal interferes with the maintenance of multiple competing stimulus representations in working memory, resulting in mutual inhibition and decreasing working memory performance (Lee, Itti, & Mather, 2012; Mather, Clewett, Sakaki, & Harley, 2016; Mather & Sutherland, 2011). In the context of statistical learning, it is possible that the statistical regularities and emotional stimuli compete for limited processing resources, leading to greater suppression of mental representations of emotional stimuli that constitute the repeating patterns. This may then deteriorate statistical learning for emotional relative to neutral information.

The present study

This study aimed to test the competing hypotheses regarding enhancing vs. impairing effects of emotional information on statistical learning. To this end, the three experiments of this study utilized a classic statistical learning paradigm in which participants first viewed an uninterrupted stream of emotional real-world visual scenes and then completed a forced-choice recognition task. Experiment 1 was designed to provide a first basic demonstration of the statistical learning effect in the context of negative information. In particular, the goal of this first experiment was to determine whether human subjects are sensitive for regularities in a continuous flow of negative visual scenes. Follow-up Experiments 2 and 3 addressed the specificity of learning regularities in streams of negative information. These experiments examined whether the strength of statistical learning differed for negative scenes compared to neutral (Experiment 2) or positive (Experiment 3) scenes. The more specific goals of these two follow-up experiments were to examine the conditions under which learning of regularities within negative information would be enhanced vs. impaired. Together, these experiments aimed to characterize the nature of statistical learning mechanisms operating on emotional material.

Experiment 1

Method

Participants

Sixty-one undergraduate students were recruited from the research participant pool (52 women; Age range: 17 – 34 years). The sample size was determined through *a priori* power analysis. The analyses (see below) were well-powered ($1\text{-}\beta=.80$, $\alpha=.05$) to detect conservative estimates of small to medium effects (Cohen's d=0.30-0.35) of statistical learning for negative information. The required sample size was increased by ~10% to account for potential dropout or equipment failure. All participants provided informed consent and received a course credit. The institutional review board approved the study protocol.

Stimuli

Twelve different negative images were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2005) based on ratings of valence (M=2.16, SD=0.26) and arousal (M=6.26, SD=0.54). The images depicted a variety of negative scenes involving human subjects (image number between brackets): a crying boy (#2900), a subway robbery (#3500), a soldier holding a gun (#6212), an assault with a knife (#6313), a carjacking (#6821), a famished child (#9040), a plane crash (#9050), a war victim (#9250), a premature infant (#3350), a fire (#9921), a car accident (#9910), and a KKK rally (#9810). The images were presented in full color.

As in previous studies (Brady & Oliva, 2008), the images were used to create four different triplets. Each triplet concerned a sequence of three IAPS images that always appeared in the same order (e.g., ABC, DEF, GHI). These sequences were randomly generated for each participant. A longer sequence of images was then created by randomly interleaving 75 repetitions of each triplet. Randomization of the triplets was constrained so that the same triplet or set of two triplets never repeated twice in a row. For example, repetitions such as ABCABC and ABCDEFABCDEF were not allowed. In addition, 100 repeat IAPS images were randomly interleaved in the stream of triplets. These repeat images presented the third image of a triplet immediately (e.g., ABCCDEF) so that the triplet structure remained intact.

Procedure

The procedure was modeled after prior statistical learning studies presenting visual real-world scenes (Brady & Oliva, 2008). Participants were seated 60 cm from a 17-inch monitor and viewed a sequence of 1,000 IAPS images. The images were presented one at a time for 500 ms with 500 ms inter-stimulus intervals (ISI). The images were centered and subtended 20.01° × 15.07° of visual angle. Participants were instructed to detect back-to-back repeats of the same image as quickly as possible by pressing a key. This cover task intended to avoid that participants would not encode the content of the pictures, and to prevent that participants would become explicitly aware of the structure in the stream of visual scenes (Brady & Oliva, 2008; Turk-Browne et al., 2005). Repetition detections were considered correct if the response was provided when the repeat image was onscreen (i.e., within 500 ms). Importantly, participants were not informed about any structure in the stream of images.

After the exposure phase, participants were asked whether they had recognized any structure in the stream (Brady & Oliva, 2008; Zhao et al., 2013). They were first asked: "*Did you notice any patterns in the stream of images?*". Because demand effects might encourage an affirmative response to this first question, participants were subsequently asked: "*If we asked you which images generally followed a certain picture, would you be able to report this?*". This second question is particularly informative to test whether participants were explicitly aware about the structure in the continuous flow of images.

Next, participants were given a surprise two-alternative forced-choice (2AFC) recognition test to examine whether participants were able to extract regularities in the continuous stream of negative images. On each test trial, participants viewed two successively presented sequences of three IAPS images. The images appeared at the center of the screen with the same duration and ISI as during the exposure phase. Each sequence was separated by a 1000 ms interval. One of the test sequences was a triplet presented during the exposure phase (e.g., ABC, DEF, GHI). The other test sequence was a foil constructed from IAPS images from three different triplets (e.g., AEI, DHC, GBF). After the presentation of the two test sequences, participants were required to choose which sequence seemed more familiar based on what they saw during the exposure phase. Each of the four triplets was tested eight times, paired twice with each of the four different foil sequences. The order of the trials was randomized and the order of the test and foil sequence was counterbalanced across trials. The percentage of triplets that was correctly chosen as familiar was used as a measure of statistical learning (Brady & Oliva, 2008; Zhao et al., 2013).

Results

Recognition of statistical regularities

In line with prior studies, the accuracy on the 2AFC test was compared to chance level to examine whether statistical learning had occurred (Brady & Oliva, 2008; Zhao et al., 2013). As shown in Figure 1, the accuracy on the surprise 2AFC test in Experiment 1 was M=65.78 (SD=17.05; SE=2.20), which was significantly higher than 50% chance, $t(59)$=7.17, p<.001, d=0.93. Thus, negative triplets were successfully discriminated from foil sequences. This result indicates that participants were on average able to extract regularities in continuous streams of negative images.

Explicit awareness about statistical regularities

When participants were asked whether they had recognized any structure in the stream, 86.67% responded “yes” to the first question (“*Did you notice any patterns in the stream of images?*”) and 35% responded “yes” the second question (“*If we asked you which images generally followed a certain picture, would you be able to report this?*”). Follow-up analyses revealed no significant differences in accuracy on the 2AFC recognition test between participants responding “no” vs. “yes” to the first question [M_{no}=72.63, SD_{no}=11.96; M_{yes}=64.73, SD_{yes}=17.55; $F(1, 58)=1.50$, $p=.226$, $d=0.47$] or second question [M_{no}=62.69, SD_{no}=15.79; M_{yes}=71.52, SD_{yes}=18.18; $F(1, 58)=3.84$, $p=.055$, $d=0.53$]. Importantly, the recognition accuracy of participations responding “no” to the first question, $t(7)=5.35$, $p=.001$, $d=1.89$, or to the second question, $t(38)=5.02$, $p<.001$, $d=0.80$, was still higher than 50% chance. This suggests statistical learning occurred even in participants who reported not to be aware of any structure in the stream of negative visual scenes.

Repetition detection accuracy

The overall accuracy on the repeat-detection trials during the exposure phase was M=75.38% (SD=13.74). This indicates that participants were attending to the unsegmented stream of IAPS images. One participant with an extremely low repetition-detection accuracy of 10% was excluded from the analyses reported above. Note that exclusion of this participant did not alter the conclusions regarding the statistical learning effect.

Interim discussion

These results extend previous demonstrations of statistical learning for neutral visual scenes (Brady & Oliva, 2008) and support the notion that human subjects are able to extract statistical regularities in flows of negative information. Interestingly, as for neutral information (Brady & Oliva, 2008; Fiser & Aslin, 2002; Turk-Browne et al., 2005), participants were able to discriminate negative triplets from foil sequences even when they reported not to be aware of any statistical structures.

However, by presenting only negative visual scenes, the observed ability to detect regularities in streams of negative information may reflect a general ability to detect regularities that is not specific to negative information. To examine the specificity of statistical learning for negative material, Experiment 2 presents triplets of negative and neutral images to examine whether statistical learning for negative is enhanced or impaired compared to statistical learning for neutral material.

Experiment 2

Method

Participants

Forty undergraduate students were recruited at Ghent University (33 women; Age range: 17 – 21 years). The sample size was determined through *a priori* power analysis. Analyses (see below) were well-powered ($1-\beta=.80$, $\alpha=.05$) to detect an estimated effect of $d\approx0.40$ for differences in statistical learning for negative vs. neutral information. This conservative effect size was chosen in light of the increased task difficulty compared to Experiment 1 where large effects were observed ($d=0.93$). Informed consent was obtained from all participants. Participants received a course credit. The institutional review board approved the study protocol.

Stimuli

The same 12 negative IAPS images from Experiment 1 were utilized. In addition, 12 neutral IAPS images were selected based on affect ratings (valence: $M=5.14$, $SD=0.43$; arousal: $M=3.89$, $SD=1.36$) ratings. Similar to the negative IAPS images, the neutral IAPS images depicted human subjects in a variety of situations (IAPS image number between brackets): a male judge (#2221), a boy solving a math problem (#2410), a tourist (#2850), a boy playing chess (#2840), a person on a car (#2870), a person's shadow (#2880), a man on a cliff (#8150), a runner (#8465), twin men (#2890), a card dealer (#7503), an office clerk (#7550), a construction worker (#7640). The images were presented in full color. Negative ($M=1.68$, $SD=0.08$) and neutral ($M=1.62$, $SD=0.17$) IAPS images were matched on image complexity (indexed by the fractal dimension), $t(11)=1.15$, $p=.276$.

The 24 IAPS images were then used to create four different triplets (cf. Experiment 1). From the sets of neutral and negative IAPS images, 6 images were randomly sampled for each participant to create 2 negative and 2 neutral triplets. A longer sequence of images was again created by randomly interleaving 75 repetitions of each triplet. The same restrictions to randomization were applied as in Experiment 1. In addition, 100 repeat IAPS images were inserted into this stream (50 repeat images for each valence category). In this experiment, either the first or the third image in a triplet was sometimes repeated immediately (e.g., ABCDDEF or ABCCDEF). This was to make repeat images even less informative for delineating triplets from one another than in Experiment 1 (Brady & Oliva, 2008).

Procedure

Participants were seated 60 cm from a 17-inch monitor and completed the statistical learning task. The instructions and exposure phase of the task were identical to Experiment 1 and prior statistical learning studies utilizing neutral visual scenes (Brady & Oliva, 2008) . The only exceptions were (a) the repetition of either the first or the third image of a triplet and (b) the manipulation of the valence of the triplets. Note that the number of triplets and triplet repetitions remained the same.

Following the exposure phase, participants were again asked whether they had recognized any structure in the stream of IAPS images. Identical to Experiment 1, participants responded to two questions: "*Did you notice any patterns in the stream of images?*" (question 1) and "*If we asked you which images generally followed a certain picture, would you be able to report this?*" (question 2).

Finally, to test whether participants were able to detect regularities in the stream of negative and neutral images, participants completed a similar surprise 2AFC recognition test as in Experiment 1. On each test trial, participants viewed two successively presented sequences of three IAPS images separated by a 1000 ms pause. One sequence was a triplet from the exposure phase (e.g., ABC, DEF). The other sequence was a foil constructed from IAPS images from the two triplets with either a negative or neutral valence (e.g., AEC, DBF). The 2AFC test sequences formed different negative and neutral triplet – foil combinations. The combinations included were: negative triplet – negative foil, negative triplet – neutral foil, neutral triplet – negative foil, and neutral triplet – neutral foil. Following the presentation of the sequences, participants were instructed to choose which sequence seemed more familiar based on the initial exposure phase. Each of the four triplets was tested eight times, paired twice with each of the four different foil sequences (2 neutral and 2 negative foil sequences). The order of the trials was randomized and the order of the test and foil sequence was counterbalanced across trials. Similar to Experiment 1 and prior work (Brady & Oliva, 2008; Zhao et al., 2013), the percentages of negative and neutral triplets that were correctly chosen as familiar were used as indexes of statistical learning. In addition, recognition accuracies of all negative/neutral triplet/foil combinations in the 2AFC test were inspected to break down the total scores.

Results

Recognition of statistical regularities

Figure 1 depicts the mean recognition accuracy rates on the surprise 2AFC test for negative and neutral triplets for Experiment 2. For negative triplets, the accuracy was M=67.50 (SD=16.52, SE=2.61). For neutral triplets, the accuracy was M=57.66 (SD=25.92, SE=4.10). The negative, $t(39)=6.70$, $p<.001$, $d=1.06$, but not the neutral, $t(39)=1.87$, $p=.069$, $d=0.30$, triplets were accurately recognized above 50% chance level. Interestingly, the accuracy on the 2AFC test for negative triplets was significantly higher than the accuracy for neutral triplets, $t(39)=2.79$, $p=.008$, $d=0.44$.

Breaking down these effects, recognition accuracies of all negative/neutral triplet/foil combinations in the 2AFC test were further inspected (see Figure 2). Comparison of accuracy rates with 50% chance level revealed that negative triplets were successfully discriminated from both negative foils (*M*=75.31, *SD*=19.91, *SE*=3.15), *t*(39)=8.04, *p*<.001, *d*=1.27, and neutral foils (*M*=74.38, *SD*=20.79, *SE*=3.29), *t*(39)=7.42, *p*<.001, *d*=1.17. This provides further evidence that statistical learning robustly occurred for regularities in sequences of negative information.

Interestingly, analysis of 2AFC trials with neutral triplets revealed that neutral triplets were discriminated from neutral foil sequences (*M*=65.94, *SD*=27.00, *SE*=4.27), *t*(39)=3.73, *p*=.001, *d*=0.59, but not from negative foil sequences (*M*=49.38, *SD*=29.82, *SE*=4.71), *t*(39)=0.13, *p*=.90, *d*=0.02. This indicates that statistical learning did occur for repeating patterns of neutral information, but that the effect diminished when recognition of learned patterns of neutral information competed with random sequences of negative information.

Examination of differences among accuracies on 2AFC trials revealed that negative triplets were discriminated from negative and neutral foils to similar extent, *t*(39)=0.45, *p*=.653, *d*=0.07. Critically, neutral triplets were recognized less well than negative triplets when presented with negative foils, *t*(39)=4.62, *p*<.001, *d*=0.73. Furthermore, when competing with neutral foil sequences, negative triplets were more accurately discriminated than neutral triplets, *t*(39)=2.03, *p*=.049, *d*=0.32. Also, neutral triplets were less well recognized when presented with negative foils than when presented with neutral foils, *t*(39)=4.48, *p*<.001, *d*=0.71. Finally, negative triplets were better discriminated from negative foils than neutral triplets were discriminated from neutral foils, *t*(39)=2.07, *p*=.044, *d*=0.33. This pattern of results consistently shows that negative triplets were better discriminated from foil sequences than neutral triplets, indicating that statistical learning is enhanced for negative compared to neutral information.

Explicit awareness about statistical regularities

When asked about the structures in the stream, 60% of the participants responded "yes" to the first question ("*Did you notice any patterns in the stream of images?*") and 27.5% responded "yes" the second question ("*If we asked you which images generally followed a* *certain picture, would you be able to report this?*").[1] Nonetheless, follow-up analyses suggested no significant differences in accuracy on the 2AFC test between participants responding "no" vs. "yes" to the first question for negative triplets [$M_{\text{no}}=63.28$, $SD_{\text{no}}=13.28$; $M_{\text{yes}}=70.31$, $SD_{\text{yes}}=18.08$; $F(1, 38)=1.77$, $p=.191$, $d=0.43$] and neutral triplets [$M_{\text{no}}= 53.13$, $SD_{\text{no}}= 23.50$; $M_{\text{yes}}= 60.68$, $SD_{\text{yes}}= 27.49$; $F(1, 38)=0.81$, $p=.374$, $d=0.29$]. Likewise, no significant differences in accuracy on the 2AFC test emerged between participants responding "no" vs. "yes" to the second question for negative triplets [$M_{\text{no}}=67.46$, $SD_{\text{no}}=14.01$; $M_{\text{yes}}=67.61$, $SD_{\text{yes}}=22.68$; $F(1, 38)=0.001$, $p=.979$, $d=0.01$] and neutral triplets [$M_{\text{no}}= 57.11$, $SD_{\text{no}}= 25.86$; $M_{\text{yes}}= 59.09$, $SD_{\text{yes}}= 27.30$; $F(1, 38)=0.05$, $p=.833$, $d=0.08$]. Importantly, the accuracies for negative triplets on the 2AFC test in "no"-responders on the first question [$t(15)=4.00$, $p=.001$, $d=1.00$] or second question [$t(28)=6.71$, $p<.001$, $d=1.25$] were still higher than 50% chance. The accuracy for neutral triplets was not different from chance in "no"-responders on both questions [question 1: $t(15)=0.53$, $p=.603$, $d=0.13$; question 2: $t(28)=1.48$, $p=.150$, $d=0.27$].

Examination of the different trials of the 2AFC task also revealed no differences between participants responding "no" vs. "yes" to both questions for any of the negative/neutral triplet/foil combinations (all F's <2.378 and p's>.131). Comparing with 50% chance, accuracy rates of "no"-responders on the first question showed that negative triplets were successfully discriminated from both negative foils ($M=71.09$, $SD=18.66$, $SE=4.67$), $t(15)=4.52$, $p<.001$, $d=1.13$, and neutral foils ($M=75.00$, $SD=22.36$, $SE=5.59$), $t(15)=4.47$, $p<.001$, $d=1.12$. In addition, neutral triplets were discriminated from neutral foils ($M=65.63$, $SD=27.58$, $SE=6.89$), $t(15)=2.27$, $p=.039$, $d=0.57$, but not from negative foils ($M=40.63$, $SD=28.32$, $SE=7.08$), $t(15)=1.32$, $p=.205$, $d=0.33$. An identical pattern of results emerged regarding the second question. Negative triplets were discriminated from negative foils ($M=76.29$, $SD=16.48$,

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[1] The endorsement rates are lower than in Experiment 1. This is likely caused by the modified presentation of the repeat images in Experiment. In this experiment (and Experiment 3), the first or the third image in a triplet was sometimes repeated immediately. In Experiment 1, only the third image was repeated. Repetition of the first and third image in a triplet makes it more difficult to delineate the triplets and to become explicitly aware of the triplets.

SE=3.06), *t*(28)=8.59, *p*<.001, *d*=1.60, and neutral foils (*M*=75.86, *SD*=19.46, *SE*=3.61), *t*(28)=7.16, *p*<.001, *d*=1.33. Again, neutral triplets were discriminated from neutral foils (*M*=66.81, *SD*=28.20, *SE*=5.24), *t*(28)=3.21, *p*=.003, *d*=0.60, but not from negative foils (*M*=47.41, *SD*=29.01, *SE*=5.39), *t*(28)=0.48, *p*=.635, *d*=0.09.

Taken together, these findings suggest that statistical learning for negative and neutral information also occurred in participants who reported that they were not aware of any repeated patterns in the stream of negative and neutral images.

Repetition detection accuracy

The overall accuracy on the repeat-detection task during the exposure phase was *M*=65.18% (*SD*=11.12). Though the repeat-detection accuracy for negative triplets *M*=62.64% (*SD*=10.24) was lower than for neutral triplets *M*=67.82% (*SD*=13.50), *t*(39)=3.76, *p*=.001, the accuracy rates indicate that participants were attending to the sequence of IAPS images. However, the difference in repetition detection accuracy could suggest that participants were attending more to neutral than negative material during exposure. While repeat-detection accuracies may be a good indicator of task compliance, they may be less appropriate to index preferential attention in the current experiment because of the fixed and short stimulus presentation and inter-stimulus interval (both 500 ms). No timely detection of image repetitions could mean that participants were not attending to the stimuli or, the opposite, were holding the negative images online in WM (interfering with repetition detection). Therefore, this finding should be interpreted with care. Importantly, the difference in repetition detection accuracy for negative and neutral repeat images was not related to differential recognition accuracy of negative and neutral triplets, *r*(40)=-.06, *p*=.706.

Interim discussion

These results extend Experiment 1 by comparing statistical learning ability of negative vs. neutral information. Participants were better at detecting sequences of negative compared to neutral visual scenes, suggesting specificity in statistical learning favoring negative information. These findings provide support the enhancement hypothesis.

Despite the bias toward negative regularities, participants were able to extract repeating sequences in neutral visual scenes. In particular, evidence for statistical learning for neutral information was observed when neutral triplets competed with neutral foils, but not when neutral triplets competed with negative foils. This suggests that the presence of random sequences of negative information may distract and reduce recognition of learned regularities occurring in neutral information.

While statistical learning may be enhanced for negative compared to neutral material, it remains unclear such a negative bias remains when regularities in negative material are simultaneously presented with positive material. Therefore, Experiment 3 presents competing triplets of negative and positive images to test whether statistical learning for negative vs. positive material is enhanced or impaired.

Experiment 3

Method

Participants

Sixty-six undergraduate students were recruited at Ghent University (56 women; Age range: 17 – 38 years). The sample size was determined through *a priori* power analysis. Informed by Experiment 2, the analyses (see below) were well-powered ($1\text{-}\beta=.80$, $\alpha=.05$) to detect a conservative estimated difference of $d\approx0.35$ between statistical learning for negative vs. positive information. Informed consent was obtained from all participants. Participants were paid 5 euro. The institutional review board approved the study protocol.

Stimuli

The same 12 negative IAPS images from Experiment 1 and 2 were utilized. In addition, 12 positive IAPS images were selected based on affect ratings (valence: *M*=7.50, *SD*=0.38;

arousal: *M*=5.89, *SD*=0.94) ratings. As the negative IAPS images, the positive IAPS images depicted human subjects in a variety of situations (IAPS image number between brackets): a baby (#2070), an older man (#2340), an older couple (#2550), a young couple (#4599), a love scene (#4660), sky-divers (#5621), a hiker (#5629),), a cliff diver (#8180), rafting (#8370), athletes (#8380), running teens (#8461), and a roller coaster (#8490). The images were presented in full color. Negative (*M*=1.68, *SD*=0.08) and positive (*M*=1.70, *SD*=0.06) IAPS images were matched on image complexity (indexed by the fractal dimension), *t*(11)=1.40, *p*=.188, and arousal levels, *t*(11)=0.85, *p*=.414.

The 24 IAPS images were then used to create four different triplets (cf. Experiment 1 and 2). From each set of positive and negative IAPS images, 6 images were randomly sampled for each participant to create 2 negative and 2 positive triplets. A longer sequence of images was again created by randomly interleaving 75 repetitions of each triplet. The same restrictions to randomization were applied as in Experiment 1. In addition, 100 repeat IAPS images were inserted into this stream (50 repeat images for each valence category). In this experiment, either the first or the third image in a triplet was sometimes repeated immediately (e.g., ABCDDEF or ABCCDEF). This was to make repeat images less informative for delineating triplets from one another than in Experiment 1 (Brady & Oliva, 2008).

Procedure

The experimental procedure was identical to Experiment 2, with the exception of the positive images that were presented instead of neutral images.

Results

Recognition of statistical regularities

As shown by Figure 1, the accuracy on the surprise 2AFC was *M*=62.69 (*SD*=20.13, *SE*=2.48) for positive triplets and *M*=67.14 (*SD*=20.49, *SE*=2.52) for negative triplets. Both positive, *t*(65)=5.12, *p*<.001, *d*=0.63, and negative, *t*(65)=6.80, *p*<.001, *d*=0.84, triplets were accurately recognized above 50% chance level. The accuracy on the 2AFC recognition test for negative triplets was not significantly higher than the accuracy for positive triplets, *t*(65)=1.67, *p*=.099, *d*=0.21.

Inspection of accuracy rates for all four negative/positive triplet/foil combinations on the 2AFC test revealed that all triplets were recognized above 50% chance level (see Figure 3). Specifically, negative triplets were successfully discriminated from both negative foils (*M*=68.37, *SD*=22.70, *SE*=2.80), *t*(65)=6.57, *p*<.001, *d*=0.81, as well as positive foils (*M*=71.59, *SD*=22.74, *SE*=2.80), *t*(65)=7.71, *p*<.001, *d*=0.95. In addition, positive triplets were discriminated from both negative foils (*M*=59.85, *SD*=24.37, *SE*=3.00), *t*(65)=3.28, *p*=.002, *d*=0.40, and positive foils (*M*=65.53, *SD*=22.47, *SE*=2.77), *t*(65)=5.61, *p*<.001, *d*=0.69. In sum, these findings suggest that statistical learning occurs for both positive and negative information.

Regarding differences in accuracy of the different 2AFC trials, analyses showed that negative triplets were discriminated from negative and positive foils to a similar extent, *t*(65)=1.07, *p*=.287, *d*=0.13. When presented with positive foil sequences, negative triplets were as accurately recognized as positive triplets, *t*(65)=1.78, *p*=.080, *d*=0.22. Similar recognition accuracies were also found for negative and positive triplets when they were paired with foil sequences of the same valence, *t*(65)=0.81, *p*=.422, *d*=0.10. Of note, positive triplets were less well recognized than negative triplets when they competed with negative foils, *t*(65)=2.47, *p*=.016, *d*=0.30. Also, positive triplets tended to be less well recognized when they competed with negative foils than when presented with positive foils, *t*(65)=1.92, *p*=.059, *d*=0.24. These findings suggest that negative and positive triplets were generally discriminated from foil sequences to a similar extent. Yet, recognition of regularities in sequences of positive information may be disturbed in when random sequences of negative information are presented.

Explicit awareness about statistical regularities

When asked about the structures in the stream, 54.5% of the participants responded "yes" to the first question ("*Did you notice any patterns in the stream of images?*") and 18.2% responded "yes" the second question ("*If we asked you which images generally followed a certain picture, would you be able to report this?*"). Again, the follow-up analyses revealed no significant differences in accuracy on the 2AFC test between participants responding "no" vs. "yes" to the first question for both negative triplets [M_{no}=66.04, SD_{no}=19.12; M_{yes}=68.06, SD_{yes}=21.79; *F*(1, 64)=0.16, *p*=.694, *d*=0.10] and positive triplets [M_{no}= 61.04, SD_{no}=19.47; M_{yes}= 64.06, SD_{yes}= 20.83; *F*(1, 64)=0.37, *p*=.548, *d*=0.15]. Likewise, no significant differences in accuracy on the 2AFC test emerged between participants responding "no" vs. "yes" to the second question for negative triplets [M_{no}=66.78, SD_{no}=20.60; M_{yes}=68.75, SD_{yes}=20.81; *F*(1, 64)=0.09, *p*=.766, *d*=0.10] and positive triplets [M_{no}= 61.46, SD_{no}= 19.94; M_{yes}= 68.23, SD_{yes}= 20.89; *F*(1, 64)=1.11, *p*=.295, *d*=0.34]. Importantly, the accuracies for negative and positive triplets on the 2AFC recognition test in "no"-responders on the first question [negative: *t*(29)=4.60, *p*<.001, *d*=0.84; positive: *t*(29)=3.11, *p*=.004, *d*=0.56] or second question [negative: *t*(53)=5.99, *p*<.001, *d*=0.82; positive: *t*(53)=4.22, *p*<.001, *d*=0.58] were still higher than 50% chance. This suggests that statistical learning for negative and positive information also occurred in participants who reported that they were not explicitly aware of any structure in the stream of images.

There were no differences between participants responding "no" vs. "yes" to each of the awareness questions for the negative/positive triplet/foil combinations of the the 2AFC task (all *F*'s <2.20 and *p*'s>.143). Comparing with 50% chance, accuracy rates of "no"-responders on the first question showed that negative triplets were successfully discriminated from negative foils (*M*=66.25, *SD*=19.74, *SE*=3.60), *t*(29)=4.51, *p*<.001, *d*=0.82, and positive foils (*M*=67.08, *SD*=21.65, *SE*=3.95), *t*(29)=4.32, *p*<.001, *d*=0.79. In addition, positive triplets were successfully discriminated from positive foils (*M*=63.75, *SD*=21.61, *SE*=3.95), *t*(29)=3.49, *p*=.002, *d*=0.64, and tended to be discriminated from negative foils (*M*=58.33, *SD*=23.75, *SE*=4.34), *t*(29)=1.92, *p*=.064, *d*=0.35. As for the second awareness check question, negative triplets were discriminated from both negative foils (*M*=68.06, *SD*=21.67, *SE*=2.95), *t*(53)=6.12, *p*<.001, *d*=0.83, and positive foils (*M*=70.37, *SD*=22.82, *SE*=3.11), *t*(53)=6.56, *p*<.001, *d*=0.89. Also, positive triplets were successfully discriminated from positive foils (*M*=63.89, *SD*=22.74, *SE*=3.09), *t*(53)=4.49, *p*<.001, *d*=0.61, as well as negative foils (*M*=59.03, *SD*=23.22, *SE*=3.16), *t*(53)=2.86, *p*=.006, *d*=0.39. This general pattern of findings suggests that statistical learning for negative and positive information occurred in participants who reported that they were not explicitly aware or be able to report of repeating patterns in the flow of negative and positive visual scenes.

Repetition detection accuracy

The overall accuracy on the repeat-detection task during the exposure phase was *M*=67.38% (*SD*=9.52). Though the repeat detection accuracy for negative triplets *M*=64.05% (*SD*=10.07) was lower than for positive triplets *M*=70.85% (*SD*=10.48), *t*(65)=7.15, *p*<.001, the accuracy rates indicate participants were attending to both sequences of IAPS images. As noted earlier, this difference in repetition detection accuracy should be interpreted with care given the features of the statistical learning task that do not allow unambiguous interpretation. Critically, the difference in repetition detection accuracy for negative vs. positive repeat images was not related to differential recognition accuracy of negative and positive triplets, *r*(66)=.18, *p*=.141.

Interim discussion

Experiment 3 extends the first two experiments by examining statistical learning of regularities in an uninterrupted flow of positive and negative visual scenes. The results showed that participants were able to detect repeating patterns in streams of negative and positive images. Thus, presentation of competing regularities in flows of negative and positive information did not impair statistical learning. The data provided evidence for the enhancement hypothesis.

Though regularities in streams of negative and positive visual scenes were generally detected with similar accuracy, it was found that recognition of learned patterns in positive material was reduced when such regularities competed with random negative information (foil sequences). This suggests that distracting negative information may influence the recognition of learned statistical regularities in positive information.

General discussion

This study furthers the understanding of how people process complex continuous input of emotional information by characterizing the nature of statistical learning of regularities in emotional information. Experiment 1 showed that participants were able to identify regularities in streams of negative visual scenes above chance level, providing initial evidence for statistical learning for negative stimuli. Experiment 2 demonstrated that participants' ability to extract statistical relations was enhanced for negative material when the continuous stream of stimuli presented both sequences of negative and neutral stimuli. Finally, Experiment 3 revealed that participants were able to identify statistical regularities in sequences of both negative and positive information when presented in one continuous flow of stimuli. This pattern of findings provides consistent evidence for statistical learning mechanisms operating on emotional material such that individuals are able to learn co-occurrences among emotional stimuli in a continuous flow of information. These findings extend prior work researching statistical learning mechanisms operating on neutral information presented in various sensory modalities (e.g., Frost et al., 2015; Krogh et al., 2013; Santolin & Saffran, 2018; Siegelman et al., 2017).

The results of the present study are consistent with the enhancement hypothesis. This hypothesis states that emotional information and statistical regularities, as two important sources of prioritization (Todd & Manaligod, 2017), have additive effects such that the emotional content of regularities facilitates its detection. Clear support for this notion was provided by the observations that recognition accuracies for negative and positive regularities were consistently higher than chance level, recognition accuracy for negative regularities was higher than for neutral regularities, and recognition accuracy for negative regularities was similar to positive regularities. Indeed, these findings are in clear contrast with the impairment hypothesis that emotional arousal may interfere with statistical learning (Mather & Sutherland, 2011). Rather than causing interference, it is more plausible that emotional information mobilizes more processing resources (cf. Mather & Sutherland, 2011; Todd et al., 2012; Vuilleumier & Huang, 2009), which may facilitate learning of repeated patterns in positive and negative information compared to neutral information. Of note, in line with prior work demonstrating statistical learning for neutral stimuli (e.g., Brady & Oliva, 2008), there was evidence that participants also learned regularities occurring in neutral visual scenes. This suggests that statistical learning is enhanced for emotional information but still operates on competing neutral information.

Interestingly, the findings also suggest that contextual factors may affect the recognition of learned statistical regularities in positive information. Although regularities in negative and positive information were discriminated from foil sequences to a similar extent, it was found that recognition of learned regularities in positive information was reduced when presented against negative foil sequences. Similar to prior research showing that emotional stimuli may reduce working memory capacity (Garrison & Schmeichel, 2018; Schweizer & Dalgleish, 2016), this finding suggests that random sequences of negative information may distract during recollection and reduce recognition of positive regularities.

Across all experiments, we found that explicit awareness of structures in the stream of stimuli did not modulate learning of regularities in negative, positive, or neutral information. It was consistently observed that recognition accuracies of statistical regularities were not significantly different between individuals who indicated to be able of reporting the structures and individuals who indicated not to be aware of any structure. This observation suggests that learning of relations among these stimuli fueled decisions on the recognition task regardless of explicit awareness. This finding accords with prior research in the context of neutral stimuli (Brady & Oliva, 2008; Fiser & Aslin, 2002; Turk-Browne et al., 2005; Zhao et al., 2013) and suggests that statistical learning mechanisms operating on emotional information could reflect a form of learning that occurs both within and outside explicit awareness.

The knowledge gained as a result of this study may cast light on the processes involved in how regularities in the emotional world can be encoded and guide predictions about emotional events. Statistical learning is often viewed as a mechanism that guides learning the covariance of causes and effects (Brady & Oliva, 2008). If someone is able to extract statistical regularities in emotional information, then one might be better at understanding the antecedents and consequences of a situation or one's own behavior, and make accurate predictions about future events. By contrast, not being able to detect structures underlying sequences of emotional events may yield a poorer understanding of a situation including less accurate predictions about potential outcomes.

Several limitations to this study should be acknowledged. First, this study utilized self-report questions as a measure of explicit awareness about structures in the streams of emotional information. Though this method has been used frequently in prior research, the use of explicit self-report to measure an implicit process may be suboptimal. Future work needs to address this limitation by using behavioral indicators of implicit learning (e.g., reaction times, anticipatory eye movements) as well as alternative tests to measure participants' awareness (Kim et al., 2009). Second, Experiment 3 was designed to detect small to moderate differences in statistical learning, but may have lacked power to detect small differences (*d*'s≈0.20-0.25) in recognition accuracies of some trials of the 2AFC task. Indeed, some contrasts were trending towards significance and may have reached the 0.05 threshold when a large sample would have been recruited. However, it is to note that most effects qualified as medium to large across all three experiments. Yet, future studies could be designed to detect small effect sizes when comparing statistical learning for different types of emotional information. Third, the diverse set of visual scenes that was utilized in all experiments did not allow investigation of emotion-specific effects. The images depicted human subjects in a variety of situation and may reflect different emotions including anger, disgust, sadness, fear, etc. While the aim of the present study was to provide a basic demonstration of statistical learning for emotional information, future work could examine statistical learning mechanisms in the context of more coherent categories of stimuli reflecting specific emotions. Finally, this study observed considerable individual differences in the recognition of statistical regularities in positive and negative information but did not identify sources of this variability. An interesting avenue for future research could be to explore whether individual differences in statistical learning for emotional information are related to psychopathology. Prior research has shown that individuals suffering from affective disorders often display a negative attention bias (e.g., Todd et al., 2012). It is plausible that individual differences in attention allocation toward negative information would be related to individual differences in extracting regularities in negative information, and that statistical learning this may play a role in various symptoms of psychopathology (e.g., hypervigilance among anxious people to detect signs of potential threat in the environment).

Despite these limitations, this study advances the understanding of how people process emotional information in important ways. This study examined whether statistical learning mechanisms operate on complex continuous input of emotional information. The results suggest that individuals are able to identify the underlying structure of continuous flows of negative and positive stimuli. This ability was enhanced for negative compared to neutral information. Importantly statistical learning occurred despite that participants were not oriented toward the regularities, performed a distracting cover task, and stimuli were presented quickly. This study may help to understand the processes that enable people to make inferences about the complex input of the emotional world.

References

Baldwin, D., Andersson, A., Saffran, J., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition*, *106*(3), 1382–1407. https://doi.org/10.1016/J.COGNITION.2007.07.005

Bourgeois, A., Chelazzi, L., & Vuilleumier, P. (2016). How motivation and reward learning modulate selective attention. *Progress in Brain Research*, *229*, 325–342. https://doi.org/10.1016/bs.pbr.2016.06.004

Brady, T. F., & Oliva, A. (2008). Statistical learning using real-world scenes. *Psychological Science*, *19*(7), 678–685. https://doi.org/10.1111/j.1467-9280.2008.02142.x

Conway, C. M., & Christiansen, M. H. (2005). Modality-constrained statistical learning of tactile, visual, and auditory sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(1), 24–39. https://doi.org/10.1037/0278-7393.31.1.24

Creel, S. C., Newport, E. L., & Aslin, R. N. (2004). Distant melodies: Statistical learning of nonadjacent dependencies in tone sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(5), 1119–1130. https://doi.org/10.1037/0278-7393.30.5.1119

Dolcos, F., Wang, L., & Mather, M. (2014). Current research and emerging directions in emotion-cognition interactions. *Frontiers in Integrative Neuroscience*, *8*, 83. https://doi.org/10.3389/fnint.2014.00083

Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 458–67. https://doi.org/http://dx.doi.org/10.1037/0278-7393.28.3.458

Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality versus modality specificity: The paradox of statistical learning. *Trends in Cognitive Sciences*, *19*(3), 117–125. https://doi.org/10.1016/J.TICS.2014.12.010

Garrison, K. E., & Schmeichel, B. J. (2018). Effects of emotional content on working memory capacity. *Cognition and Emotion*, 1–8. https://doi.org/10.1080/02699931.2018.1438989

Hamann, S. (2001). Cognitive and neural mechanisms of emotional memory. *Trends in Cognitive Sciences*, *5*(9), 394–400. https://doi.org/10.1016/S1364-6613(00)01707-1

Kim, R., Seitz, A., Feenstra, H., & Shams, L. (2009). Testing assumptions of statistical learning: Is it long-term and implicit? *Neuroscience Letters*, *461*(2), 145–149. https://doi.org/10.1016/J.NEULET.2009.06.030

Krogh, L., Vlach, H. A., & Johnson, S. P. (2013). Statistical learning across development: Flexible yet constrained. *Frontiers in Psychology*, *3*, 598. https://doi.org/10.3389/fpsyg.2012.00598

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2005). *International Affective Picture System (IAPS): Digitized photographs, instruction manual and affective ratings*. Gainesville, FL: University of Florida.

Le Pelley, M. E., Mitchell, C. J., Beesley, T., George, D. N., & Wills, A. J. (2016). Attention and associative learning in humans: An integrative review. *Psychological Bulletin*, *142*(10), 1111–1140. https://doi.org/10.1037/bul0000064

Lee, T.-H., Itti, L., & Mather, M. (2012). Evidence for arousal-biased competition in perceptual learning. *Frontiers in Psychology*, *3*, 241. https://doi.org/10.3389/fpsyg.2012.00241

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39*, e200. https://doi.org/10.1017/S0140525X15000667

Mather, M., Mitchell, K. J., Raye, C. L., Novak, D. L., Greene, E. J., & Johnson, M. K. (2006). Emotional arousal can impair feature binding in working memory. *Journal of*

Cognitive Neuroscience, *18*(4), 614–625. https://doi.org/10.1162/jocn.2006.18.4.614

Mather, M., & Sutherland, M. R. (2011). Arousal-biased competition in perception and memory. *Perspectives on Psychological Science*, *6*(2), 114–33. https://doi.org/10.1177/1745691611400234

Pool, E., Brosch, T., Delplanque, S., & Sander, D. (2015). Attentional nias for positive emotional stimuli : A meta-analytic investigation. *Psychological Bulletin*, *142*(1), 79–106. https://doi.org/10.1037/bul0000026

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Santolin, C., & Saffran, J. R. (2018). Constraints on statistical learning across species. *Trends in Cognitive Sciences*, *22*(1), 52–63. https://doi.org/10.1016/J.TICS.2017.10.003

Schweizer, S., & Dalgleish, T. (2016). The impact of affective contexts on working memory capacity in healthy populations and in individuals with PTSD. *Emotion*, *16*(1), 16–23. https://doi.org/10.1037/emo0000072

Siegelman, N., Bogaerts, L., & Frost, R. (2017). Measuring individual differences in statistical learning: Current pitfalls and possible solutions. *Behavior Research Methods*, *49*(2), 418–432. https://doi.org/10.3758/s13428-016-0719-z

Talmi, D. (2013). Enhanced emotional memory: Cognitive and neural mechanisms. *Current Directions in Psychological Science*, *22*(6), 430–436. https://doi.org/10.1177/0963721413498893

Todd, R. M., Cunningham, W. A., Anderson, A. K., & Thompson, E. (2012). Affect-biased attention as emotion regulation. *Trends in Cognitive Sciences*, *16*(7), 365–372. https://doi.org/10.1016/j.tics.2012.06.003

Todd, R. M., & Manaligod, M. G. M. (2017). Implicit guidance of attention: The priority state space framework. *Cortex*. https://doi.org/10.1016/j.cortex.2017.08.001

Turk-Browne, N. B., Isola, P. J., Scholl, B. J., & Treat, T. A. (2008). Multidimensional visual statistical learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(2), 399–407. https://doi.org/10.1037/0278-7393.34.2.399

Turk-Browne, N. B., Jungé, J. A., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General*, *134*(4), 552–564. https://doi.org/10.1037/0096-3445.134.4.552

Vuilleumier, P., & Huang, Y.-M. (2009). Emotional attention: Uncovering the mechanisms of affective biases in perception. *Current Directions in Psychological Science*, *18*, 148–152. https://doi.org/10.2307/20696018

Yiend, J. (2010). The effects of emotion on attention: A review of attentional processing of emotional information. *Cognition and Emotion*, *24*(1), 3–47. https://doi.org/10.1080/02699930903205698

Zhao, J., Al-Aidroos, N., & Turk-Browne, N. B. (2013). Attention is spontanesouly biased toward regularities. *Psychological Science*, *24*(5), 667–677. https://doi.org/10.1177/0956797612460407

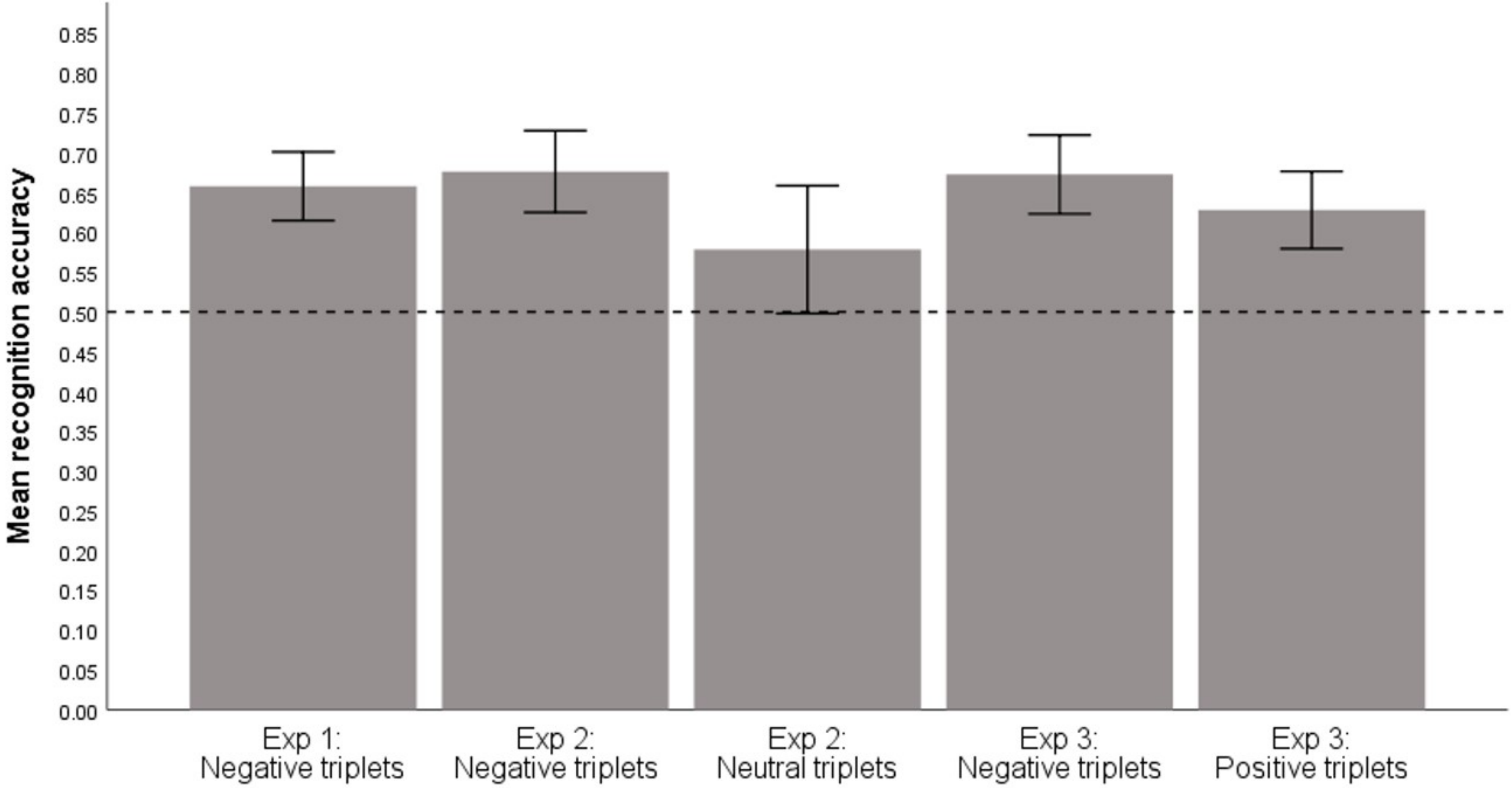

Figure 1. Mean recognition accuracy (proportion correct responses) on the 2AFC task for Experiments 1, 2, and 3. Errors bars indicate 95% confidence intervals.

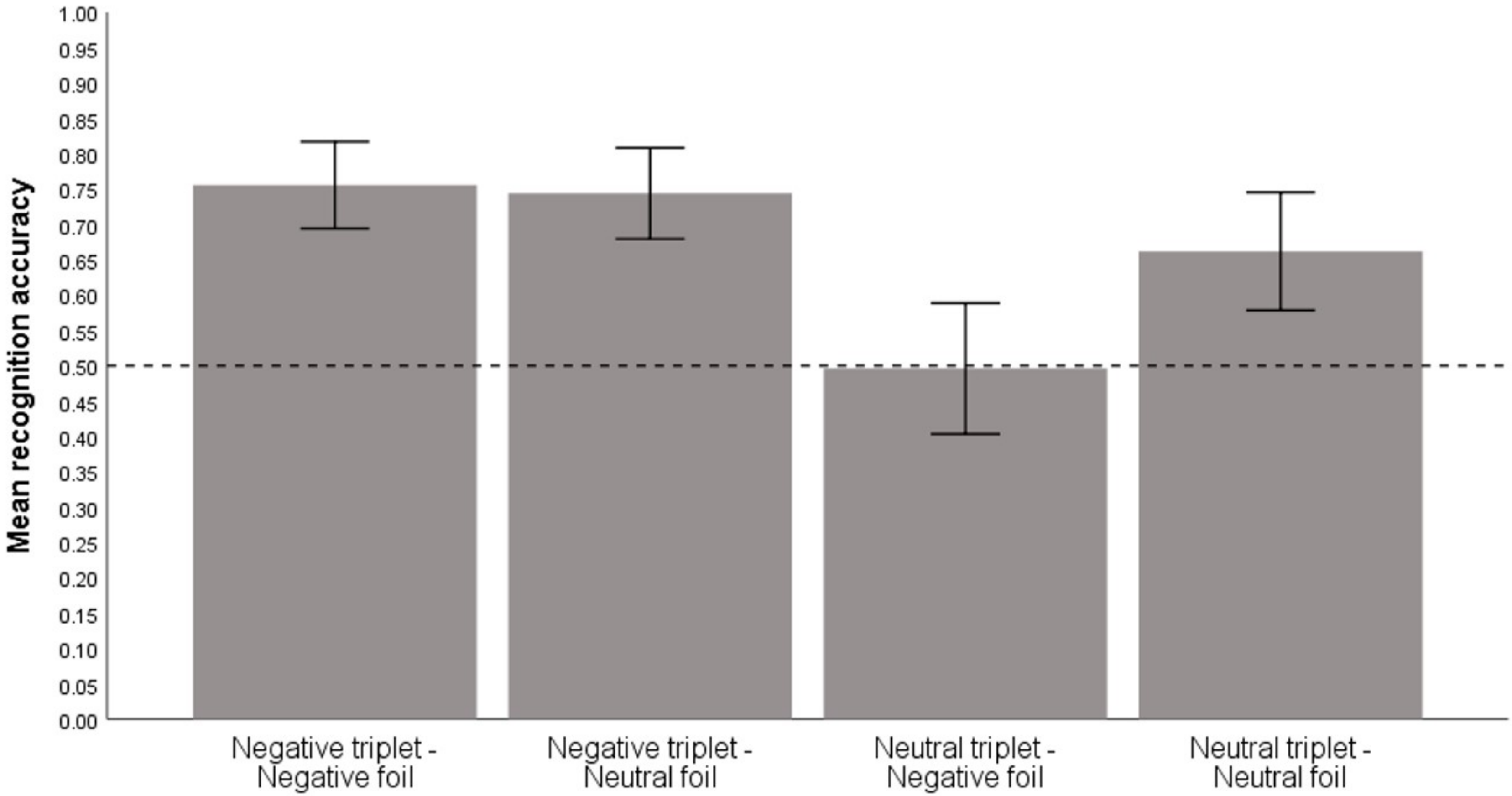

Figure 2. Mean recognition accuracy (proportion correct responses) on the trials of the 2AFC task for Experiment 2. Errors bars indicate 95% confidence intervals.

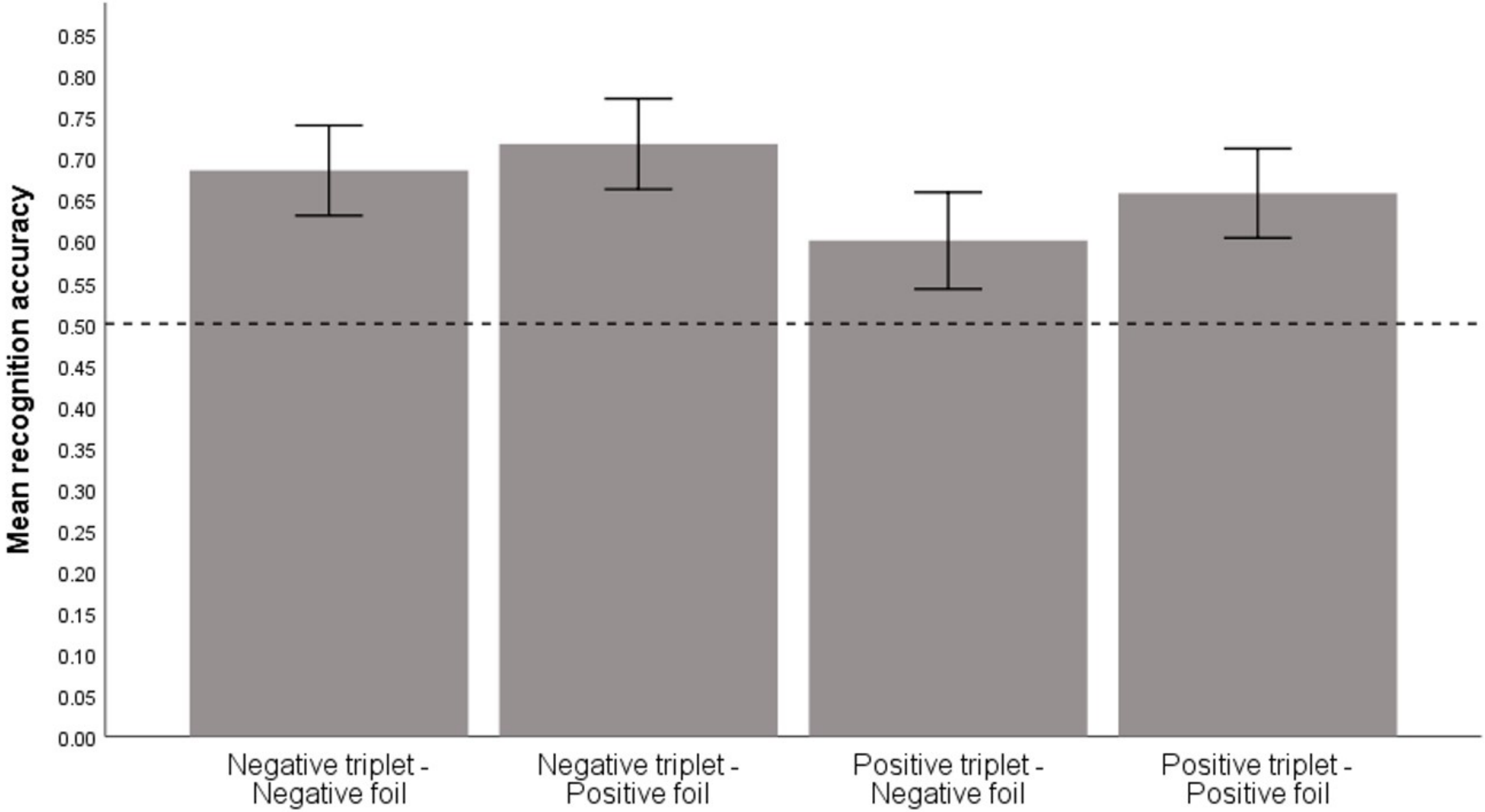

Figure 3. Mean recognition accuracy (proportion correct responses) on the trials of the 2AFC task for Experiment 3. Errors bars indicate 95% confidence intervals.