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Individual patterns of visual exploration predict the extent of fear generalization in humans

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Abstract

Generalization of fear is considered an important mechanism contributing to the etiology and maintenance of anxiety disorders. Although previous studies have identified the importance of stimulus discrimination for fear generalization, it is still unclear to what degree overt attention to relevant stimulus features might mediate its magnitude. To test the prediction that visual preferences for distinguishing stimulus aspects are associated with reduced fear generalization, we developed a set of facial stimuli that was meticulously manipulated such that pairs of faces could either be distinguished by looking into the eyes or into the region around mouth and nose, respectively. These pairs were then employed as CS+ and CS- in a differential fear conditioning paradigm followed by a generalization test with morphs in steps of 20%. Shock expectancy ratings indicated a moderately curved fear generalization gradient that is typical for healthy samples but its shape was altered depending on individual attentional deployment: Subjects who dwelled on the distinguishing facial features faster and for longer periods of time exhibited less fear generalization. Although both, pupil and heart rate responses also showed a generalization gradient, with pupil diameter and heart rate deceleration increasing as a function of threat, these responses were not significantly related to visual exploration. In total, the current results indicate that the extent of explicit fear generalization depends on individual patterns of attentional deployment. Future studies evaluating the efficacy of perceptual trainings that aim to augment stimulus discriminability in order to reduce (over-)generalization seem desirable. Data, materials, experimental & analysis scripts can be accessed via <https://osf.io/4gz7f/>.

Keywords: fear generalization; attention; social; faces; temporal dynamics

1 Introduction

Anxiety disorders greatly contribute to the psychological burden in the United States and Europe (Kessler et al., 2005; Wittchen et al., 2011) and consequently, efforts have been increased to identify mechanisms that contribute to their etiology and maintenance. One such mechanism is fear generalization. Anecdotally described 100 years ago in the well-known case study of “little Albert” (Watson & Rayner, 1920), fear generalization describes the phenomenon that learned fear is not restricted to those exact stimuli with which an aversive event was originally paired but extends to perceptually or conceptually similar ones (Dymond, Dunsmoor, Vervliet, Roche, & Hermans, 2015).

For example, Lissek and colleagues (2008) employed circles of intermediate sizes (generalization stimuli; GS) to form a gradient between a conditioned stimulus (CS+) that was paired with an electric shock (unconditioned stimulus, US) and a second stimulus (CS-) that was never followed by the US. These intermediate circles were presented to healthy subjects after fear acquisition. Interestingly, both perceived risk of US and startle responses increased with similarity to the CS+ in a specific manner: For stimuli closer to the CS-, responses were consistently low while they increased rapidly for stimuli with high similarity to the CS+. This curved response pattern was interpreted as healthy subjects generalizing fear only to those intermediate circles that resembled the CS+ the most. In comparison, patients who suffer from pathological fear usually show more linear gradients that form an earlier and more steady increase, generalizing fear even to stimuli similar to the CS-. This has been demonstrated for patients with panic disorder (Lissek et al., 2010), post-traumatic stress disorder (Kaczurkin et al., 2017; Lissek & Grillon, 2012), and generalized anxiety disorder (Lissek et al., 2014 but see Tinoco-González et al., 2015). Generalization gradients have been mostly described for subjective ratings and startle responses

(e.g., Lissek et al., 2010; Lissek et al., 2014), but they have also been observed in skin conductance responses (e.g., Dunsmoor, Kroes, Braren, & Phelps, 2017; Schiele et al., 2016), changes in pupil diameter (e.g., Greenberg, Carlson, Cha, Hajcak, & Mujica-Parodi, 2013), and phasic heart rate decelerations (Ahrens et al., 2016).

While individual differences in perceptual fear generalization are stable over time (Torrents-Rodas et al., 2014) and have been shown to predict anxiety symptomatology (Lenaert et al., 2014), the mechanism underlying this phenomenon is still under debate. It is often implicitly assumed that it merely reflects the individual's inability to perceptually distinguish between the CS+ and the generalization stimuli (e.g. Lissek, 2012). Struyf and colleagues (2017) tested this assumption explicitly in a large sample by adding a discrimination task at the end of generalization trials. Results indicated that perceptual errors occur predominantly in a biased way, i.e., GSs are frequently mistaken for CSs but not vice versa. Furthermore, this perceptual confusion alters US-expectancy accordingly, resulting in increased expectancy ratings for generalization stimuli (see also Zaman, Ceulemans, Hermans, & Beckers, 2019).

Contrasting with the perceptual confusion hypothesis, Onat and Büchel (2015) used functional neuroimaging within a fear generalization paradigm. They observed that activation of the anterior insula was sharply tuned to the CS+ and thus exhibited a narrower generalization profile than skin conductance responses or shock expectancy ratings. This pattern of results indicates that threat identification could in principle be performed unambiguously and the authors therefore concluded that fear generalization is an active process that integrates uncertainty signals from object-sensitive visual areas to compute the behavioral or autonomic output (for similar results of sharp CS-tuning see McTeague, Gruss, & Keil, 2015; Stegmann, Ahrens, Pauli, Keil, & Wieser, 2020). Another study using auditory stimuli in conjunction with multivoxel pattern

analysis, however, was able to find neural generalization profiles in primary auditory cortices and the amygdala that support the perceptual confusion hypothesis of fear generalization and also highlights the role of affective modulation of stimulus representations in these regions (Laufer, Israeli, & Paz, 2016). Consequently, it is still unclear to what extent fear generalization is driven by low-level perceptual or by higher-level decision-making processes.

In this study, we examined the influence of attentional processes on perceptual fear generalization. Interestingly, patterns of visual exploration are heritable (Constantino et al., 2017; Kennedy et al., 2017) and highly stable across long periods of time (Mehoudar, Arizpe, Baker, & Yovel, 2014). Additionally, these consistent viewing patterns seem to be domain-specific and they correlate with perceptual performance, e.g., regarding face recognition abilities (de Haas, Iakovidis, Schwarzkopf, & Gegenfurtner, 2019). Moreover, healthy subjects automatically attend to specific facial features, predominantly the eyes and mouth, to facilitate the recognition of emotional expressions (Scheller, Büchel, & Gamer, 2012) and this mechanism seems to be biased in social phobia (Boll, Bartholomaeus, Peter, Lupke, & Gamer, 2016). Finally, using manipulated line drawings that included predefined distinguishing features, Baruch and colleagues (2014) demonstrated that visual and spatial priming of relevant features facilitated object recognition by enhancing local attentional deployment. In summary, distinguishing features attract visual attention and facilitate recognition of objects, faces, and emotional expressions. Hence, we expected that selective attention to distinguishing facial features may also increase discriminability between faces and thereby reduce generalization of fear.

To investigate this role of attentional processes on the extent of fear generalization, we created a novel stimulus set of facial photographs that was meticulously manipulated such that pairs of faces could be distinguished only by looking either into the eyes or in the region around

the mouth and nose. These pairs were then employed as CS+ and CS− respectively within a fear generalization paradigm. After fear acquisition, morphs in steps of 20% between CS+ and CS− were presented to test generalization of fear. Trial-by-trial shock expectancy ratings, heart rate, electrodermal activity, and eye movements were measured. To analyze generalization gradients, we calculated linear deviation scores (Kaczurkin et al., 2017) that describe the degree of curvature and thereby provide an efficient index to compare different gradients (see Gradient Analysis below). We sought to replicate a curved generalization gradient that is typical for healthy samples (Ahrens et al., 2016; Lissek et al., 2010). Furthermore, we expected that subjects would predominantly focus on eyes compared to other facial features (Mehouder et al., 2014) but that they would as well be able to adaptively shift their focus toward diagnostic mouths and noses. Our main hypothesis was that participants who deploy more attention toward diagnostic facial features would also show fear generalization gradients that are curved more strongly, thus indicating less generalization. Since the experimental protocol was not specifically adjusted for the registration of skin conductance data (see Discussion), methods and results regarding this measure are reported in the Supplementary Material.

2 Materials and Methods

2.1 Participants

Forty-eight healthy subjects (37 female) participated in the study for course credit or financial compensation (15 €). Sample size was chosen to detect medium to large relations ($\beta \geq .4$) at $\alpha = 5\%$ with a power of 80%. For one individual, the experiment was aborted due to insufficient performance in the initial discrimination task (see Procedure). Three further participants were

1 excluded since their pain ratings of the US had decreased to non-painful levels until the end of the
2 generalization phase.

3 The final sample consisted of 44 individuals (35 female; $age = 25.7 \pm 5.0$ years) that
4 exhibited low levels of social anxiety ($SIAS = 19.7 \pm 8.0$). All participants reported to be free of
5 any diagnosed mental or neurological disorder and gave written informed consent. The study was
6 approved by the local ethics committee of the Department of Psychology at the University of
7 Würzburg and was performed in accordance with the Declaration of Helsinki.

8 **2.2 Stimulus Materials**

9 **2.2.1 Visual Stimuli.** Edited facial portrait photographs with neutral expression were used
10 as stimuli. The pictures had a resolution of 642×676 pixels and were taken from the Oslo Face
11 Database (Chelnokova et al., 2014; Leknes, 2014). Pairs of photographs with the same gender and
12 similar skin color were selected and edited with the GNU Image Manipulation Program (GIMP)
13 such that either the eyes or both mouth and nose were copied from one face to the other while
14 keeping all other pixels identical. The original photograph and the edited picture thus differed only
15 in the specified area and were later used as CS+ and CS− (assignment counterbalanced
16 alternatingly across participants). This factor, which we call *diagnostic region* (cf. Scheller et al.,
17 2012), was introduced to require a flexible strategy of facial exploration in order to successfully
18 distinguish between different pairs of stimuli. In total, one male and one female pair was created
19 for each diagnostic region (eyes vs. mouth/nose). For each subject, two out of the four pairs were
20 chosen such that one male and female pair as well as both diagnostic regions were present. It was
21 counterbalanced whether a participant encountered a female or male pair with diagnostic eyes and
22 which faces of these pairs were assigned to comprise the two CS+s and CS−s. We also generated
23 morphs in steps of 20% between both faces of each pair with Abrosoft FantaMorph software to

comprise a generalization dimension. Participants viewed the pictures on a 24" Asus VG248QE screen that was set to a resolution of 1920×1080 pixels and was placed 53 centimeters away from the subjects' eyes. Hence, the stimuli filled an area of 19.0°×20.0° with the face occupying a visual field of approximately 9.5°×10.0°.

2.2.2 Electrotactile Stimuli. Aversive stimuli were applied to the dorsum of the left hand via a Wasp Electrode (Specialty Development, Bexley, UK) which was connected to a bipolar DC-stimulator model DS7A (Digitimer Ltd., Hertfordshire, UK). Each stimulation consisted of three trains of 2 ms pulses, separated by 48 ms.

2.3 Procedure

After completion of the informed consent form, subjects were seated inside an acoustically shielded cabin and performed a discrimination task to assure that they were able to perceptually distinguish between the stimuli that were sought to be used as CSs in the fear generalization paradigm (see the Supplementary Material, Discrimination Task). In succession, electrodes for the measurement of heart rate and electrodermal activity as well as for pain application were attached. The intensity of the painful stimulus was then individually adjusted to a moderate level (six or seven on an eleven-point scale ranging from *0 = no sensation* over *4 = minimally painful* to a theoretical maximum of *10 = worst pain imaginable*; see the Supplementary Material, Pain Calibration). Next was a training task that should ensure that subjects perform their trial-by-trial shock expectancy rating within the specified time window (see the Supplementary Material, Timing Training). Thereafter, the fear generalization task was conducted (see below). Before subjects were debriefed and reimbursed, they completed the Social Interaction Anxiety Scale (SIAS; Mattick & Clarke, 1998; Stangier, Heidenreich, Berardi, Golbs, & Hoyer, 1999), and a

questionnaire targeting demographic data in paper form. All behavioral tasks were run on a desktop computer using PsychoPy 1.85.6 (Peirce, 2007).

Fear Generalization Task. The fear generalization task consisted of three phases: habituation, fear acquisition, and fear generalization (cf. Lissek et al., 2008). During habituation, each of the four selected facial stimuli (one male and one female pair differing in the eye or mouth/nose region, respectively, in counterbalanced fashion) was presented four times without any electrotactile stimulation. Fear acquisition followed up seamlessly consisting of 32 trials in total. The two stimuli that were assigned to denote the CS+s (i.e., one stimulus of the male and female pair, respectively, in counterbalanced fashion) were reinforced in 75% of the cases. After a short break and recalibration of the eye-tracker, the last phase started. During generalization, four intermediate stimuli between the CS+ and the CS- (morphs in steps of 20%) were also presented for each stimulus pair. These generalization stimuli (GS) spanned the generalization continuum from CS- across GS1 through GS4 to CS+. Each of the ten non-CS+s was presented eight times during the generalization phase. The two CS+s, however, were presented 16 times with a 50% reinforcement rate in order to reduce extinction. Thus, the generalization phase consisted of 112 trials. The fear generalization task in total included 160 trials. Each trial consisted of a face being presented for 6 seconds. After 4 seconds, a rating prompt appeared at the bottom of the screen for 2 seconds. Subjects were asked to indicate the perceived likelihood of an electrotactile stimulation occurring at the end of the trial on a 5-point scale (*1 = no shock, 3 = uncertain, 5 = shock certain*) but they were not told about different phases or contingencies. The painful stimulation was applied or omitted 5.85 seconds after stimulus onset. If subjects pressed too early or too late, the answer was marked as invalid. A fixation cross in the center of the screen was

- 1 depicted during the inter-trial-interval with its duration following a uniform distribution between
 2 2 and 4 seconds to minimize anticipation effects (cf. Figure 1).

3 **Figure 1.** Schematic depiction of a trial sequence. Trials included a random inter-trial interval with fixation
 4 cross, the stimulus presentation of six seconds in total, and a rating prompt overlay appearing four seconds
 5 after stimulus onset (for details, see Figure S1 in the Supplementary Material). Aversive electrotactile
 6 stimulation was applied or omitted on top of visual presentation during the last 0.15 seconds (i.e., 5.85
 7 seconds after stimulus onset). All stimuli can be viewed at <https://osf.io/wgqnj/wiki/home/>.
 8

9 2.4 Data Recording and Processing

10 **2.4.1 Shock Expectancy Ratings.** Behavioral responses were collected during every trial
 11 with a keyboard that had all buttons removed except for the five response keys (QWERTY-Layout:
 12 Space = 1, L = 2, Semicolon = 3, Apostrophe = 4, and Right Shift = 5). Participants placed their
 13 right hand on the keyboard such that each finger corresponded to one of the keys (thumb on Space,
 14 pinky on Right Shift). The shock expectancy data of two subjects were excluded since more than
 15 25% of their ratings were missing during generalization phase.

16 **2.4.2 Eye-Tracking.** Eye movements and pupil size were recorded with an EyeLink 1000
 17 Plus system (SR Research Ltd., Ottawa, Ontario, Canada) in tower mount mode. Eye-tracker and
 18 screen were positioned on top of a table that could be easily adjusted for the height of the
 19 participants. The right eye of participants was sampled at a rate of 1000 Hz (left eye for one subject

1 due to calibration issues). The eye-tracker was calibrated prior to the beginning of the habituation
2 phase and before the generalization phase (see Procedure). For one participant, no eye-tracking
3 was performed because of insufficient calibration quality.

4 Eye-tracking data were split into saccades and fixations using EyeLink's default parser
5 options. A saccade was defined as an eye-movement of speed beyond 30 °/s or an acceleration
6 exceeding 8000 °/s² (default parameters). Time periods between saccades were defined as
7 fixations. Results were exported into text files and processed further in R 3.5.1. Similar to our
8 previous research (e.g., End & Gamer, 2017; Flechsenhar, Larson, End, & Gamer, 2018; Rösler,
9 End, & Gamer, 2017), an iterative drift correction algorithm was applied to the spatial coordinates
10 of each subject, separately for both experimental blocks: For every trial, the last 300 ms before
11 stimulus onset were considered as the baseline during which subjects were instructed to fixate the
12 fixation cross in the center of the screen. All fixations within this time window were averaged
13 (weighted by their duration). Subsequently, the smallest and largest values were temporarily
14 removed from the distribution of baseline values and were marked as invalid when they deviated
15 more than 3 standard deviations from the mean of the distribution of remaining baseline values.
16 Valid and invalid baselines were then retained or excluded, respectively, and the procedure was
17 repeated until no more baseline location was marked as invalid. Afterwards, the coordinates of all
18 fixations throughout trials were realigned to the baseline of their respective trial or by the average
19 of all valid baselines in the current block if the baseline was determined invalid. If more than 25%
20 of baselines of a participant needed interpolation during generalization phase, the eye-tracking
21 data were excluded from analysis. However, this was not necessary for any subject. On average,
22 8.7% of trials ($SD = 5.5\%$) needed interpolation. After drift correction, regions of interest (ROIs)
23 were defined for every face pair according to their non-identical pixels. To standardize ROI size,

the superset of ROIs within the same diagnostic features (eyes vs. mouth/nose) was used for all stimuli (i.e., if a pixel was different within the respective feature for *any* pair, it was included in the ROI). Finally, the relative cumulative dwell time per ROI and the latency until the first fixation into each ROI (diagnostic and non-diagnostic) were computed within the first 4000 ms after stimulus onset, i.e. until presentation of the visual rating prompt. Dwell times were calculated for the whole duration of 4000 ms as a measure of sustained attention but we also computed them for consecutive 500 ms bins to analyze temporal characteristics of visual exploration. Resulting values were divided by the total sum of fixation durations to yield proportions.

2.4.3 Pupillary Responses. Pupil diameter was recorded simultaneously to eye movements (see Eye-Tracking). Processing was then performed in R 3.5.1 using the edfR-package (Hubbard, 2018) for data import. After linearly interpolating blink periods, trial-level time series were down-sampled to 100 Hz and filtered using a low-pass filter with a cutoff frequency of 2 Hz and a roll-off of 12 dB/octave. Subsequently, values were converted from arbitrary units to mm according to Hayes and Petrov (2016) and baseline-corrected with respect to the last second preceding stimulus onset. Finally, pupillary responses were quantified as the mean change in pupil diameter between 500 and 4000 ms after stimulus onset.

2.4.4 Electrocardiography. An electrocardiogram was obtained using three adhesive SilverTRACE ECG electrodes (Vyair Medical, Mettawa, IL, USA) placed underneath the right clavicle and the left costal arch, as well as a ground electrode at the right costal arch. Data were recorded with the Biopac MP160 system and AcqKnowledge 5.0 (BioPac Systems, Goleta, CA, USA) with a sampling rate of 500 Hz.

Processing was performed in R 3.5.1. The maxima of cyclic electrocardiac activity (R-peaks) were detected semi-automatically according to their amplitude with an option of manual

1 editing. The heart rate in beats per minute was calculated out of the resulting R-R intervals.
2 Electrocardiographic data of one participant were excluded due to excessive extrasystoles
3 ($\approx 3/\text{min}$). Remaining artifacts were interpolated by the average heart rate change of adjacent R-R
4 intervals (6 occurrences within the remaining data). To account for interindividual differences in
5 tonic heart rate, change scores relative to the last second prior stimulus onset were calculated (cf.
6 Pupillary Responses) for bins of 0.5 seconds until 5.5 seconds after stimulus onset.

7 **2.4.5 Gradient Analysis.** During the generalization phase, a gradient was created for each
8 diagnostic region ranging from the CS⁻ across the four morphs to the CS⁺ (see Procedure). The
9 indicated expectancy ratings and the physiological data can thus be mapped as a function of
10 perceptual proximity to the CS⁺ denoting assumed threat level. Since the shape of this resulting
11 graph was of primary interest, linear deviation scores (LDS; Kaczurkin et al., 2017) were
12 calculated as the difference between the mean response to CSs and the mean response to the
13 generalization stimuli. This measurement has proven useful in several studies (e.g., Stegmann et
14 al., 2019; van den Akker, Schyns, Breuer, van den Broek, & Jansen, 2019) and effectively indexes
15 if the fear gradient follows a steady, linear pattern (LDS = 0), or whether it exhibits curvature
16 upwards (less generalization, LDS > 0) or downwards (more generalization, LDS < 0). This
17 measure of the fear profile was then used as criterion in a linear model with subjects' fixation
18 patterns as predictor.

19 **2.4.6 Statistical Analysis.** For each experimental phase (habituation, acquisition, and
20 generalization), shock expectancy ratings and physiological data were averaged according to the
21 position of the depicted face along the generalization gradient (factor *threat level*; ranging from
22 CS⁻ across the 4 generalization stimuli, GS1 through GS4, to the CS⁺). Since no generalization
23 stimuli were shown during habituation and acquisition, differences between CS⁻ and CS⁺ were

analyzed using paired t-tests in these two phases. For the generalization phase, repeated measures ANOVAs with factor *threat level* (CS–, GS1 through GS4, CS+) were employed. Furthermore, eye tracking data were analyzed using a two-step procedure: First, hypotheses were tested in a confirmatory analysis using the minimal design specification consisting of factors *ROI* (eyes vs. mouth/nose) and *diagnosticity* (diagnostic vs. non-diagnostic). Secondly, data were explored using the maximum design specification including the additional factors *threat level* (CS–, GS1 through GS4, CS+) and *trial time* (0 to 4 sec in bins of 0.5 sec). The Greenhouse-Geisser procedure (Greenhouse & Geisser, 1959) was applied for potential violations of the sphericity assumption in repeated-measures ANOVAs involving more than one degree of freedom in the numerator. Follow-up tests were performed two-sidedly unless there was a directional prediction by one of our hypotheses.

To test our main hypothesis that patterns of visual exploration are related to individual differences in fear generalization, we calculated linear mixed models with random intercepts for subjects and two fixed effects: the relative cumulative dwell time into the diagnostic ROI and an effect-coded (Singmann & Kellen, 2020) factor with two levels denoting if the eyes or the mouth/nose region were diagnostic for the current stimulus. The criteria were the linear deviation scores (cf. Gradient Analysis) of shock expectancy, heart rate and pupil diameter change gradients, respectively.

3 Results

3.1 Shock Expectancy Ratings

During habituation, there was no significant difference between the expected probability of a painful stimulation following photographs that were later to become CS+ vs. CS–

($t(41) = -0.96$, $p = .341$, $d = -0.15$, 95% CI $[-0.45, 0.16]$). After acquisition, the association between CS+ and the electric shock was perceived as higher than for the CS- ($t(41) = 13.32$, $p < .001$, $d = 2.06$, 95% CI $[1.51, 2.59]$), confirming successful fear acquisition. The average course of shock expectancy ratings across the whole experiment can be seen in Figure 2a.

To analyze the generalization phase, a within-subjects ANOVA was conducted with the factor *threat level* (CS-, GS1 through GS4, CS+). Results indicated a significant main effect of *threat level* ($F(5, 200) = 118.54$, GG- $\epsilon = .55$, $p < .001$, $\eta_p^2 = .74$, 95% CI $[.65, .79]$). In Figure 2b, the corresponding fear gradient is depicted that exhibits a curved shape and shows a monotonic increase from CS- across the GSs to the CS+. Follow-up one-sided t-tests indicated that every two adjacent levels were significantly different from each other ($ts \geq 2.60$, $ps \leq .007$, $ds \geq 0.40$).

3.2 Pupillary Responses

Since expectancy ratings indicated successful acquisition of conditioned responses, the analyses of the physiological data primarily focused on the generalization phase. For analyses of physiological data during habituation and acquisition, see the Supplementary Material.

To analyze phasic modulations of pupil size, a within-subjects ANOVA with the factors *threat level* and *diagnostic region* was conducted. Pupillary responses differed significantly according to their *threat level* ($F(5, 210) = 2.31$, GG- $\epsilon = .84$, $p = .045$, $\eta_p^2 = .05$, 95% CI $[.00, .06]$). We conducted follow-up one-sided t-tests and found increasing pupil sizes across the generalization gradient: Relative to the CS-, increased pupillary responses were detected for the CS+ ($t(42) = 3.13$, $p = .002$, $d = 0.48$, 95% CI $[0.16, 0.79]$) and the GS3 ($t(42) = 1.78$, $p = .041$, $d = 0.27$, 95% CI $[0.03, 0.58]$). The remaining faces, including GS4, which was closest to the CS+, did not differ significantly from the CS- ($ts \leq 0.77$, $ps \geq .223$, $ds \leq 0.12$). The grand average waveform and the derived fear generalization gradient can be seen in Figure 3.

Figure 2. Shock expectancy ratings for each threat level (GS: generalization stimulus). Data are depicted a) on a trialwise basis across the progression of the experiment and b) averaged across the generalization phase. Confidence bands and error bars indicate standard errors of between-subjects estimates. Semi-transparent dots indicate data of individual participants.

Figure 3. Mean pupillary responses for each threat level (GS: generalization stimulus) within the generalization phase. Data are depicted a) along the trial progression and b) averaged between 500 and 4000 ms after stimulus onset. Confidence bands and error bars indicate standard errors of between-subjects estimates.

3.3 Heart Rate

Since the grand average temporal dynamics revealed a contingent heart rate deceleration following stimulus onset (cf. Figure 4a), data were collapsed across temporal bins for further analysis and a within-subjects ANOVA with the factor *threat level* was conducted. We found that heart rate modulation significantly depended on the *threat level* of stimuli ($F(5, 210) = 5.16$, $\text{GG-}\epsilon = .84$, $p < .001$, $\eta_p^2 = .11$, 95% CI [.02, .18]). Follow-up one-sided t-tests revealed an increase in heart rate deceleration along the fear gradient: Compared to the CS–, the CS+ and the generalization stimulus resembling it most closely (GS4) elicited significantly more cardiac slowdown (CS+: $t(42) = 2.78$, $p = .004$, $d = 0.42$, 95% CI [0.11, 0.73]; GS4: $t(42) = 3.41$, $p < .001$, $d = 0.52$, 95% CI [0.20, 0.84]). The remaining GSs did not differ significantly from the CS– ($ts \leq 1.54$, $ps \geq .066$, $ds \leq 0.23$). The resulting gradient is depicted in Figure 4b.

Figure 4. Average heart rate changes for each threat level (GS: generalization stimulus) within the generalization phase. Data are depicted a) along the trial progression and b) averaged across time bins within each trial. Confidence bands and error bars indicate standard errors of between-subjects estimates.

3.4 Eye-Tracking Data

To test our hypotheses concerning average fixation preferences during generalization, we first conducted a 2×2 within-subjects ANOVA with the factors *ROI* (eyes vs. mouth/nose) and *diagnosticity* (diagnostic vs. non-diagnostic) on average dwell times as dependent measure. As expected, we found a significant main effect of *ROI* ($F(1, 42) = 35.47, p < .001, \eta_p^2 = .46, 95\% \text{ CI } [.23, .61]$) that was driven by subjects, on average, looking more into the eyes ($M = 59.6\%$) compared to the mouth and nose ($M = 35.0\%$) even if the latter were diagnostic. This was accompanied by the hypothesized main effect of *diagnosticity* ($F(1, 42) = 37.24, p < .001, \eta_p^2 = .47, 95\% \text{ CI } [.24, .62]$) indicating that diagnostic facial features triggered more attentional allocation ($M = 54.1\%$) than non-diagnostic ones ($M = 40.5\%$). There was also a small but significant interaction of the two factors ($F(1, 42) = 5.55, p = .023, \eta_p^2 = .12, 95\% \text{ CI } [.00, .30]$) which was due to subjects fixating slightly more on *any* ROI (in contrast to other parts of the visual display) during the presentation of stimuli with diagnostic mouths and noses ($M = 95.3\%$) compared to when eyes were diagnostic ($M = 93.9\%$). All effects are summarized in Figure 5a.

To further explore the temporal development of effects, we employed a 2×2×6×8 within-subjects ANOVA with the additional factors *threat level* (CS−, GS1 through GS4, CS+) and *trial time* (0 to 4 sec in bins of 0.5 sec) in addition to the already mentioned factors *ROI* (eyes vs. mouth/nose) and *diagnosticity* (diagnostic vs. non-diagnostic). The extended model confirmed the previous main effects of *ROI* ($F(1, 42) = 32.49, p < .001, \eta_p^2 = .44, 95\% \text{ CI } [.21, .59]$) and *diagnosticity* ($F(1, 42) = 41.42, p < .001, \eta_p^2 = .50, 95\% \text{ CI } [.27, .64]$). The effect of *diagnosticity*, however, was superseded by a sizeable interaction with *trial time* ($F(5, 210) = 44.45, \text{GG-}\epsilon = .66, p < .001, \eta_p^2 = .52, 95\% \text{ CI } [.40, .60]$). As can be seen in Figure 5b, orienting toward diagnostic facial features was strongest within 500 to 1000 ms but this temporal modulation only lasted until

1500 ms after stimulus onset. Since further effects were considerably smaller in magnitude and did not relate to the current hypotheses, they are summarized in the Supplementary Material.

3.5 Influence of Attention on Fear Generalization

In a first model, we tested whether the curvature of shock expectancy ratings as depicted by the linear deviation score (see Gradient Analysis) could be predicted by the relative cumulative dwell time into the diagnostic ROI and additionally included an effect-coded (Singmann & Kellen, 2020) factor denoting if eyes or the region around mouth and nose were diagnostic for the current stimulus. The analysis revealed the hypothesized effect that longer dwell into diagnostic regions was associated with less fear generalization ($\beta = .30$, 95% CI [.07, .50], $t(50.27) = 2.57$, $p = .007$ one-tailed, Figure 6a). This association was neither moderated by the diagnostic region ($\beta = -.05$, 95% CI [-.17, .42], $t(77.69) = -0.37$, $p = .711$) nor did the latter predict the extent of generalization ($\beta = .14$, 95% CI [-.27, .17], $t(43.07) = 1.28$, $p = .209$). Since the exploratory analysis of the eye-tracking data indicated that early processes would be of special importance, we calculated a second linear mixed model using the square root of the latency until the first fixation into the diagnostic ROI as index for early attentional allocation (note that we used the square root of latencies to normalize the data, but similar effects emerged when relying on the raw data). This analysis yielded a negative association between the latency of first fixations on diagnostic facial features and fear generalization ($\beta = -.35$, 95% CI [-.53, -.15], $t(59.11) = -3.47$, $p < .001$ one-tailed, Figure 6b). This relationship was again not altered by the diagnostic region ($\beta = -.03$, 95% CI [-.25, .20], $t(74.58) = -0.26$, $p = .800$) and the latter did not affect fear generalization ($\beta = .08$, 95% CI [-.23, .38], $t(41.75) = -0.26$, $p = .356$). Hence, participants who directed their gaze faster toward distinguishing facial features exhibited less fear generalization.

Figure 5. Relative cumulative dwell times. Panel a) depicts the data as a function of ROI (eyes vs. mouth/nose) and diagnosticity of the respective ROI. In panel b), the temporal dynamics as revealed by an explorative ANOVA can be seen. Error bars and confidence bands indicate standard errors of between-subjects estimates. Horizontally stacked dots indicate data of individual participants.

Figure 6. Scatter plots for linear deviation scores of shock expectancy ratings during generalization. Data are depicted as a function of a) relative cumulative dwell time and b) the square root of the latency until the first fixation on the diagnostic ROI. Confidence bands indicate 95% confidence intervals of regression line estimates.

Further analyses of fear generalization profiles in pupillary responses, however, neither revealed a significant effect of the cumulative dwell time into diagnostic ROIs ($\beta = -.17$, 95% CI $[-.38, .05]$, $t(82) = -0.47$, $p = .220$) nor of the latency of the first diagnostic fixation ($\beta = -.07$, 95% CI $[-.28, .15]$, $t(82) = -0.57$, $p = .560$). Other predictors also did not reach statistical significance ($|\beta|s \leq .17$, $|t|s \leq 1.24$, $ps \geq .217$). Likewise, generalization of cardiac modulation could not be predicted by cumulative diagnostic dwell ($\beta = -.02$, 95% CI $[-.27, .23]$, $t(61.57) = -0.18$, $p = .860$), by the latency of the first fixation into a diagnostic ROI ($\beta = .03$, 95% CI $[-.20, .25]$, $t(75.25) = 0.23$, $p = .818$), or by any other factor ($|\beta|s \leq .10$, $|t|s \leq 0.68$, $ps \geq .501$).

4 Discussion

In this study, we tested the association of individual patterns of attentional allocation and fear generalization profiles by utilizing manipulated pairs of facial photographs that differed specifically within the eyes or in the region around mouth and nose. Results indicated that our healthy sample showed a moderately curved fear generalization gradient regarding shock expectancy ratings but its shape was altered depending on individual visual exploration: Subjects who dwelled on the distinguishing region of stimuli faster and for longer periods of time exhibited less fear generalization (i.e., more curvature of fear generalization gradients). This may indicate that stimulus discrimination plays an important role in the generalization of fear. Furthermore, even though subjects showed the expected tendency to mostly look at eyes, they were able to shift towards other facial features if the latter were diagnostic. An exploratory analysis revealed that effects were greatest for early fixations during the first 1500 milliseconds after stimulus onset. We

1 also observed increased pupil dilation and larger decelerative heart rate responses as a function of
2 threat level but the resulting gradient was not predicted by patterns of visual exploration.

3 The hypothesized relation between cumulative dwell time into diagnostic regions and the
4 extent of fear generalization (as measured by shock expectancy ratings) was significant.
5 Nevertheless, our exploratory analysis of the eye-tracking data revealed that dwelling on
6 distinguishing facial features occurred predominantly between 500 and 1500 milliseconds after
7 stimulus onset. Hence, during the majority of the trial, fixations were not guided by diagnostic
8 value of facial features but unanimously attracted by the region of the eyes. Consequently, a
9 measure relying more strongly on early attentional mechanisms, such as the latency of the first
10 fixation into the critical region, might be better suited to index attentional allocation towards
11 diagnostic features.

12 This also suggests that a modification of early visual patterns could be a promising tool to
13 sharpen perception and thereby diminish fear generalization (cf. Ehlers & Clark, 2000). Ginat-
14 Frolich and colleagues (2017) provided initial evidence that a perceptual training can indeed
15 decrease fear generalization in healthy subjects. Moreover, discrimination trainings can also
16 diminish avoidance responses of generalization stimuli close to the CS– even in the absence of
17 changes in US-expectancy (Lommen et al., 2017). On the other hand, such trainings might only
18 target perceptual and not conceptual generalization of fear. Future studies should evaluate to what
19 extent such training effects rely on a modulation of visual exploration and whether such tasks may
20 help to ameliorate pathological overgeneralization.

21 In general, the current data providing evidence for the importance of stimulus
22 discrimination processes in fear generalization seem to be at odds with the results of Onat and
23 Büchel (2015) since they showed that patterns of insula activity differed significantly between the

1 CS+ and even highly similar generalization stimuli despite fear generalization in behavioral
2 responses. Additionally, a region in the inferotemporal cortex showed a tuning profile that
3 emphasizes the difference between CSs and intermediate generalization stimuli and hence encoded
4 ambiguity. They concluded that fear generalization is not the mere result of stimulus confusion but
5 an active integration of threat identification and evaluation of uncertainty. Our results, however,
6 are in line with other findings indicating that perception has some predictive value with respect to
7 the amount of fear generalization (see also Laufer et al., 2016; Struyf et al., 2017; Zaman et al.,
8 2019). Maybe these findings can be reconciled in an integrative model that acknowledges
9 perceptual processes as well as active decision making in the generalization of fear responses at
10 different levels of the processing hierarchy (cf. Struyf et al., 2017). In fact, attentional processes
11 might act as a mediator and indicate whether fear generalization will occur because of stimulus
12 confusion (i.e., when diagnostic stimulus features receive little attention) or is due to a “better safe
13 than sorry” strategy employed by the organism (i.e., despite sufficient visual exploration of
14 diagnostic features). Therefore, future research should elucidate the influence of attentional
15 allocation on the neural representation of the fear gradient since relevant brain regions might be
16 differently affected by an attentional modulation of tuning functions.

17 Regarding the physiological data, we found a different pattern than Ahrens and colleagues
18 (2016). In their study, healthy participants showed a fear generalization gradient in electrodermal
19 activity but virtually no change in heart rate toward any stimulus. Our data, however, did indicate
20 differential cardiac fear responses in healthy subjects (for an overview on fear bradycardia see
21 Roelofs, 2017) while we did not observe this for skin conductance (see Supplementary Material).
22 One reason for this is that we did not optimize the experimental design for the measurement and
23 analysis of skin conductance responses. Since the primary outcome measures respond quickly to

1 visual stimulation, we chose to keep the inter-trial-interval rather short. This, however, resulted in
2 large overlap of skin conductance responses to the face stimuli, the ratings, and the US. Hence,
3 our data does not permit a valid isolation of electrodermal responses to the onset of the
4 photographs. This interpretation is supported by the pattern of pupil responses in the current study,
5 that reflected differences in threat value after the acquisition phase and mirrored the generalization
6 gradient that was also observed for heart rate deceleration. Since these pupil responses are driven
7 by sympathetic nervous system activity (Bradley et al., 2008) – similar to the skin conductance
8 responses observed in other studies – it seems sensible to assume that the current stimulus timing
9 was not optimal for recordings of electrodermal activity.

10 The current study has several strengths including the use of carefully controlled stimulus
11 material in an eye-tracking experiment to elucidate the contribution of attentional processes to fear
12 generalization. However, some limitations should also be acknowledged: First, the employment of
13 facial stimuli introduced the observed bias towards the eye region regardless of its diagnosticity.
14 Hence, it remains unclear how the current results will generalize to different stimulus material
15 such as objects, animals, or complex scenes. Researchers have highlighted the uniqueness of face
16 processing for a long time, emphasizing the role of configural information in contrast to feature-
17 specific cognition (Farah, Wilson, Drain, & Tanaka, 1998; Kanwisher, 2000; Young, Hellawell,
18 & Hay, 2013). Even though facial recognition may be more than the sum of multiple feature-based
19 analyses, our research indicates that attention to single facial features exerts predictive power on
20 perceptual generalization of fear across faces.

21 Second, similar to previous studies, we observed highly consistent generalization profiles
22 in behavioral responses that were even evident on the level of single trials (cf. Figure 2a) but found
23 much weaker and more variable gradients on the physiological level (Ahrens et al., 2016;

1 Dunsmoor et al., 2017; Lissek et al., 2010; Lissek et al., 2014; Schiele et al., 2016; Stegmann et
2 al., 2019). Apart from potential shortcomings of the experimental design regarding the
3 measurement of skin conductance data (see above), this finding most likely reflects differences
4 between measures in signal-to-noise ratio. Although this aspect is difficult to reconcile in future
5 studies, it seems to be important to acquire data from larger samples in order to examine whether
6 influences of visual patterns on physiological fear generalization gradients are indeed absent or
7 could be uncovered by increasing statistical power.

8 Third, this study explicitly focused on perceptual generalization and did therefore not
9 consider conceptual or symbolic processes. Consequently, the relative importance of active
10 inference with respect to fear generalization (in contrast to stimulus confusion) cannot be evaluated
11 here. Moreover, although we believe that it is the most plausible interpretation of the current data,
12 we could not explicitly test whether reduced fear generalization following enhanced visual
13 exploration of diagnostic regions was indeed related to improved stimulus discrimination (cf.
14 Struyf et al., 2017). Thus, although we observed a significant association between visual attention
15 and fear generalization, the current correlational design does not permit to assume causality. For
16 example, individuals who experience greater generalization could also have less motivation to
17 explore diagnostic aspects of the stimulus display. However, due to the temporal order of visual
18 modulation by diagnosticity occurring very early after stimulus onset and the expectancy rating
19 being prompted only seconds later, we deem a top-down modulation of gaze behavior by fear
20 generalization implausible.

21 To sum up, the current study demonstrated that visual exploration patterns play an
22 important role in fear generalization. Subjects who quickly and extensively looked at
23 distinguishing features displayed less generalized fear. Given that generalization patterns differ

1 greatly between individuals (Stegmann et al., 2019) and were supposed to represent a risk for the
2 development of or a marker of current psychopathology (Ahrens et al., 2016; Lissek et al., 2010;
3 Lissek et al., 2014), it seems highly interesting to apply the current experimental paradigm to risk
4 populations or patient groups to determine to what extent maladaptive visual processing might
5 explain variability in fear generalization gradients in such populations. The current data also
6 indicate that individuals who suffer from pathological overgeneralization of fear might benefit
7 from tailored trainings that aim to modify their exploration behavior such that stimulus
8 discrimination is increased. Such applications seem very promising for novel therapeutic strategies
9 in the domain of anxiety disorders.

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Conflict of Interest

The authors report no potential conflict of interest.

Supplement to:

Individual patterns of visual exploration predict the extent of fear generalization in humans

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Materials, data, and results can be accessed via <https://osf.io/4gz7f/>

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Electrodermal Activity

Method

Skin conductance was measured using a constant voltage system (0.5 V) with two 22/10 mm Ag/AgCl electrodes (Berger Medizintechnik GmbH, Gleisdorf, Österreich) filled with 0.5 % NaCl electrolyte gel (PAR Medizintechnik GmbH & Co. KG, Berlin, Germany) that were placed on the thenar and hypothenar eminences of the left hand. Data were collected via the same apparatus as cardiac activity with a sampling rate of 500 Hz.

Further processing was implemented in R 3.5.1. We adhered to the procedure by Ahrens et al. (2016) to obtain comparable results. In order to identify electrodermal non-responders, subjects' responses to the unconditioned stimuli were evaluated as the difference between the maximum and minimum electrodermal activity within the first 5 seconds after administration of electric shocks. Differences less than 0.1 μ S were scored as zero. Participants' electrodermal responses were only analyzed further if their average reaction to the painful stimulus exceeded 0.1 μ S and more than 50% of responses to the electric stimulation were non-zero. Due to these criteria, electrodermal data of 10 subjects were excluded. Subsequently, skin conductance responses (SCRs) to the photographs were scored as the difference between the maximum and minimum activity within the first 8 seconds after stimulus onset (i.e., the minimum time before presentation of the next stimulus). Differences less than 0.1 μ S were scored as zero and trials containing or following a painful stimulus were excluded in order to avoid overlapping of unconditioned responses.

Since substantial overlap between individual skin-conductance responses has to be expected (see Discussion), we also reanalyzed the data using Ledalab 3.4.9 (Benedek & Kaernbach, 2010). This toolbox decomposes the continuous electrodermal activity into tonic and phasic components. Focusing on the phasic electrodermal activity, the average driver was determined within a response window of 0.5 to 3 seconds after stimulus onset (minimum amplitude of 0.1 μ S). Again, subjects were only analyzed further if more than 50% of responses

to the electric shock were non-zero, leading to exclusion of 8 individuals. Individually determined SCR amplitudes and phasic components of electrodermal responding as calculated by Ledalab were log-transformed to reduce the skew of the amplitude distribution.

Results

SCR amplitudes in the generalization phase were analyzed using a 6×2 within-subjects ANOVA with factors *threat level* and *diagnostic region*. Responses were on average different from zero as indicated by a significant intercept ($F(1, 33) = 78.18, p < .001, \eta_p^2 = .70$) but they were not predicted by either factor or their interaction ($F_s \leq 1.51, p_s \geq .209$).

Since no differential fear response was observed in skin conductance reactivity, it is not surprising that electrodermal fear generalization profiles were also not predicted by the cumulative dwell time into diagnostic ROIs ($\beta = .11, t(62) = 0.63, p = .532$) or by the latency of the first fixation ($\beta = -.04, t(62) = -0.25, p = .806$). Other effects also did not reach significance ($|\beta|s \leq .24, |t|s \leq 1.57, p_s \geq .121$).

Employing the same ANOVA on the deconvoluted data did not change the results. Aside from a significant intercept ($F(1, 34) = 61.22, p < .001, \eta_p^2 = .64$), no other statistically significant effects were observed ($F_s \leq 1.15, p_s \geq .335$).

Further Methods

Before starting the generalization paradigm, participants completed several preparatory tasks to ensure that they could perceptually distinguish the employed stimuli, to calibrate the intensity of the electrotactile stimulation and to practice the timing of behavioral responses during the task. These tasks are described in detail in the following.

Discrimination Task. Since the stimulus material was perceptually highly similar, the experiment started with a discrimination task that was run with two pairs of stimuli that were to be employed as CS+ and CS– in the subsequent fear generalization paradigm. At the beginning of the task, the four selected pictures were shown in succession for 6 seconds each with their respective response button, separated by a fixation cross for 1 second. After having viewed each stimulus and the according response button once, participants were asked to indicate at the end of consecutive trials via button press which picture they have just seen. After the response, feedback was provided for 2 seconds. Every picture was presented five times, totaling to ten repetitions per pair and 20 trials in total. If a subject achieved less than 80% correct answers for any of the two pairs, the task was repeated and if necessary, the selected pairs were switched until the discrimination criterion was satisfied.

Pain Calibration. After the setup of the electrodes (see Data Recording and Processing), the pain calibration procedure was conducted. Subjects were exposed to two alternately ascending and descending trains of electrotactile stimuli. The first impulse started at an intensity of 0.25 mA and was adjusted in steps of 0.25 mA. In succession to each stimulation, participants indicated their sensation on an eleven-point scale ranging from *0 = no sensation* over *4 = minimally painful* to a theoretical maximum of *10 = worst pain imaginable*. The intensity was increased during ascending trains until a 4 or higher was indicated and amperage was decreased again until stimulation was not perceived as painful anymore. For each of the four trains, the minimum intensity that still obtained a painful sensation was identified, the results were averaged across trains and augmented by 50%. If this

intensity did not lead to a moderately painful sensation denoted by a six or higher on the scale, amperage was slightly adjusted once more with consultation of the subjects. After the experiment, an electrotactile stimulus of the same intensity was again applied and participants were asked to report their sensation using the same eleven-point scale as before. The average US intensity that was applied during the experiment amounted to 1.26 ± 0.90 mA and resulted in moderate pain ratings right after calibration (6.4 ± 0.5) and until after the experiment (5.3 ± 0.9). The decline in US painfulness across the experiment was significant ($t(43) = 7.95$, $p < .001$, $d = 1.20$) as well as an increase in variance ($F(43, 43) = 0.33$, $p < .001$).

Timing Training. Having calibrated the aversive electrotactile stimulation, a training phase was conducted with geometric shapes in order to get subjects accustomed to the experimental task that included a trial-by-trial rating of shock expectancies. We used three geometric shapes each with a height of 400 pixels: a green circle, a blue square, and a red equilateral triangle rotated by 180° . In the training phase, we established a contingency between the shapes and the pain stimulation of 0%, 50%, and 100% respectively. The trial structure was identical to the Fear Generalization Task (cp. Figure 1) except that a brief feedback of 1 second with the participant's rating was displayed after the painful stimulation was applied or omitted. If subjects pressed too early or too late, the answer was marked as invalid and an according feedback was provided. Every shape was presented four times in a randomized order. If participants had more than 2 invalid responses out of 12 trials in total, the procedure was explained again and repeated.

Wie wahrscheinlich folgt ein Schmerzreiz?

1	-	2	-	3	-	4	-	5
kein Reiz		unsicher			Reiz sicher			
Leertaste		L		Ö		Ä		Shift (rechts)

Figure S1. Exemplary depiction of a trial with original rating prompt in German [“How likely does a painful stimulus follow?”]. The response scale ranges from 1 = *no stimulus* across 3 = *unsure* to 5 = *stimulus certain*. The corresponding keys on the German keyboard layout are space, L, Ö, Ä, and right shift respectively.

Physiological Responses during Habituation & Acquisition

Pupillary Responses

While pupil responses did not differ between faces during habituation ($t(42) = 0.12$, $p = .904$, $d = 0.02$, 95% CI $[-0.28, 0.32]$), a sizeable effect emerged during acquisition with pupil dilation being significantly greater for CS+ compared to CS- ($t(42) = 5.29$, $p < .001$, $d = 0.81$, 95% CI $[0.46, 1.15]$). This effect decreased in magnitude during the generalization phase but remained statistically significant ($t(42) = 3.13$, $p = .002$, $d = 0.48$, 95% CI $[0.16, 0.79]$).

Heart Rate

During habituation, there was no significant difference between phasic heart rate changes in response to faces that later became a CS+ or CS- ($t(42) = -1.47$, $p = .148$, $d = -0.22$, 95% CI $[-0.53, 0.08]$). Averaging across the trials of the acquisition phase, there was still no difference between CSs ($t(42) = -1.44$, $p = .157$, $d = -0.22$, 95% CI $[-0.52, 0.08]$). Descriptively, the effect during acquisition even pointed into the opposite direction than expected, i.e., greater deceleration for CS- ($p = .921$, one-tailed). Only during the generalization phase, a significant difference between CS+ and CS- was detected ($t(42) = 2.78$, $p = .008$, $d = 0.42$, 95% CI $[0.11, 0.73]$).

Discussion

Pupillary responses and heart rate changes showed different temporal dynamics across the experiment. While modulations in pupil size emerged quickly during acquisition and already declined again in the generalization phase, threat-specific cardiac deceleration built up more slowly such that it could only be reliably detected in the last stage of the experiment. It is unclear, however, whether the weakening of differential pupillary responses was due to habituation effects or to the drop in US-contingency from 75% (acquisition) to 50% (generalization). Additionally, future research should elucidate if threat-contingent heart rate decelerations are not only slower to acquire but also more resistant to extinction.

Extended models (generalization phase)

Shock Expectancy Ratings

In order to further analyze the generalization phase, a 6×2 within-subjects ANOVA was conducted with the factors *threat level* (CS–, GS1 through GS4, CS+) and *diagnostic region* (eyes vs. mouth/nose). Along with the already discussed main effect of *threat level* ($F(5, 200) = 118.49$, $GG-\varepsilon = .59$, $p < .001$, $\eta_p^2 = .75$, 95% CI [.65, .79]), we also found an unexpected marginally significant interaction of *threat level* $\times$ *diagnostic region* ($F(5, 200) = 2.26$, $GG-\varepsilon = .59$, $p = .087$, $\eta_p^2 = .05$, 95% CI [.00, .15]). Follow-up t-tests revealed greater threat expectancy specifically for the GS1 if the diagnostic feature was comprised by the eyes compared to mouth and nose ($t(41) = 3.08$, $p = .004$, $d = 0.47$, 95% CI [0.15, 0.79]). Except for the same tendency for the CS– ($t(41) = 1.49$, $p = .143$, $d = 0.23$, 95% CI [–.08, .54]), no other influence of the diagnostic region within threat-levels was found ($|t|s \leq 0.48$, $ps \geq .637$). The main effect of *diagnostic region* was not significant ($F(1, 41) = 0.56$, $p = .458$, $\eta_p^2 = .01$, 95% CI [.00, .10]). Consequently, the diagnostic region had little impact on subjective ratings, indicating similar difficulty of perceptual discriminability between pairs.

Heart Rate

For the heart rate changes, the same 6×2 within-subjects ANOVA with factors *threat level* and *diagnostic region* was conducted. The main effect of *threat level* ($F(5, 210) = 5.16$, $GG-\varepsilon = .84$, $p < .001$, $\eta_p^2 = .11$, 95% CI [.02, .18]) was already discussed in the main article. Effects including the diagnostic region did not reach significance ($F_s \leq 0.96$, $ps \geq .443$).

Eye-Tracking Data

To explore potential temporal dynamics within the fixation behavior, we employed a $2 \times 2 \times 6 \times 8$ within-subjects ANOVA with factors *ROI* (eyes vs. mouth/nose), *diagnosticity* (diagnostic vs. non-diagnostic), *threat level* (CS–, GS1 through GS4, CS+) and *trial time* (0 to

4 sec in bins of 0.5 sec). The remaining effects that were not discussed in the manuscript are described here.

The already discussed impact of *diagnosticity* was also modulated by an interaction with the *threat level* of the stimulus ($F(5, 210) = 5.72$, $GG-\epsilon = .80$, $p < .001$, $\eta_p^2 = .12$, 95% CI [.03, .20]). Subjects exhibited less attention toward diagnostic regions in the middle of the fear gradient (esp. GS2 & GS3) compared to its extreme poles (CS- & CS+ but also GS4) (see Figure S2a). Also, a significant three-way interaction of *diagnosticity* $\times$ *threat level* $\times$ *trial time* emerged ($F(35, 1470) = 2.28$, $GG-\epsilon = .49$, $p = .002$, $\eta_p^2 = .05$, 95% CI [.01, .06]) indicating that the attenuated exploration of diagnostic features within the center of the fear gradient was particularly pronounced between 500 and 1000 ms (see Figure S4a). Furthermore, a main effect of *trial time* was found ($F(7, 294) = 13.21$, $GG-\epsilon = .25$, $p < .001$, $\eta_p^2 = .24$, 95% CI [.8, .38]) that was traced back to participants mostly fixating areas of the visual display outside of any ROI during the very beginning and end of a trial (see Figure S2b). The main effect of *threat level* was also significant ($F(5, 210) = 2.90$, $GG-\epsilon = .75$, $p = .027$, $\eta_p^2 = .06$, 95% CI [.00, .13]) indexing that across the whole trial, subjects dwelled outside of ROIs mostly for faces in the middle of the fear gradient (GS2 & GS3), to a lesser extent also while viewing safety signals (CS- & GS1), and least for threatening pictures (CS+ & GS4) (see Figure S2c).

Figure S2. Visualization of ANOVA effects: a) *diagnosticity* $\times$ *threat level*, b) main effect of *trial time*, and c) main effect of *threat*. Confidence bands indicate 95% confidence intervals of between-subjects estimates.

Building upon the previously mentioned main effect of *ROI* denoting visual preference for eyes compared to mouth and nose, an interaction with *trial time* was found ($F(7, 294) = 4.52$, $GG-\varepsilon = .35$, $p = .008$, $\eta_p^2 = .10$, 95% CI [.01, .20]). The bias towards eyes was attenuated between 500 and 1000 ms (see Figure S3a). The *ROI* effect was further modulated by an interaction with *threat level* ($F(5, 210) = 3.06$, $GG-\varepsilon = .84$, $p = .017$, $\eta_p^2 = .07$, 95% CI [.00, .13]) indicating that gaze toward eyes was slightly diminished at the more threatening half of the gradient (GS3 to CS+) (see Figure S3b). The three-way interaction of *ROI* $\times$ *threat level* $\times$ *trial time* was also significant ($F(35, 1470) = 2.32$, $GG-\varepsilon = .47$, $p = .002$, $\eta_p^2 = .05$, 95% CI [.01, .06]) yet again indicating that the aforementioned effect was strongest within the time frame between 500 and 1000 ms (see Figure S4b). Lastly, a marginally significant interaction of *diagnosticity* $\times$ *ROI* $\times$ *trial time* emerged ($F(5, 297) = 2.13$, $GG-\varepsilon = .55$, $p = .081$, $\eta_p^2 = .05$, 95% CI [.00, .11]) further classifying the two-way interaction from the confirmatory analysis. The already discussed greater amount of dwell on any ROI compared to the remainder of the display during the presentation of faces with diagnostic mouths and noses only occurred within the first 500 ms (see Figure S3c), possibly due to the proximity of this ROI to the fixation cross. No other statistically significant effects were found ($F_s \leq 1.13$, $p_s \geq .325$).

Figure S3. Visualization of ANOVA effects: a) $ROI \times trial\ time$, b) $ROI \times threat\ level$, and c) the marginal $diagnosticity \times ROI \times trial\ time$ simplified as the temporal progression of the difference score between the relative dwell times on any ROI for stimuli with diagnostic mouth & nose area minus diagnostic eyes (cp. $diagnosticity \times ROI$ in confirmatory analysis). Confidence bands indicate 95% confidence intervals of between-subjects estimates.

Figure S4. Visualization of ANOVA effects: a) *diagnosticity* $\times$ *trial time* $\times$ *threat level* and b) *ROI* $\times$ *trial time* $\times$ *threat level*. Confidence bands indicate 95% confidence intervals of between-subjects estimates.

Influence of Visual Exploration on Fear Generalization

The explorative multiple regression analysis on the shock expectancy gradient using the square root of latencies of first fixations into the diagnostic region yielded highly significant predictive value ($\beta = -.35$, 95% CI $[-.53, -.15]$, $t(59.11) = -3.47$, $p < .001$ one-tailed). Without this normalization, the effect was almost identical ($\beta = -.34$, 95% CI $[-.51, -.14]$, $t(62.83) = -3.29$, $p < .001$ one-tailed). Other predictors did not reach statistical significance ($|\beta|s \leq .07$, $|t|s \leq 0.65$, $ps \geq .519$). The respective scatter plot can be seen in Figure S5.

Figure S5. Scatter plot for linear deviation scores of shock expectancy ratings during generalization as a function of the latency until the first fixation on the diagnostic ROI. Confidence bands indicate 95% confidence intervals of regression line estimates.

References

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