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„Physiological reactions to fear of spiders:

Presenting the SpiDa database“

verfasst von / submitted by

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Abstract

Specific phobias can severely limit the quality of life of affected individuals. Given their high prevalence, finding feasible and evidence-based therapeutic approaches to phobias is of clinical importance. The current state of the art treatment is exposure therapy, where a therapist presents feared stimuli to the patient.

To model and potentially automatize exposure therapy, we conceptualised it as a dynamic closed-loop system that assesses the patient's fear state (sensor), and updates the stimulus intensity so that arousal levels are optimal for maximizing clinical efficacy (controller). We measured physiological signals to improve the assessment of the current fear state and developed an input (stimulus) – output (fear) mapping for spider phobia to provide the controller with stimuli: the SpiDa database.

55 pre-screened participants were confronted with 175 luminance-matched pictures of spiders, while physiological signals were recorded. After each picture, they were asked to rate the level of fear it induced.

Results from machine learning predictions show that two input variables are contributing most to predicting fear states: the average rating of the current stimulus across participants, and how the current participant had rated previous images. A simple model taking into account these two input variables can on average predict 60% of the variance of fear ratings for previously unseen stimuli.

We conclude that drawing not only on current signals, but also on participants' previous states and a well-defined stimulus space is most important when designing a controller for future closed loop approaches in therapy and fear research. In support of this, we will make all stimuli and the corresponding reactions publicly available.

Zusammenfassung

Spinnenphobie ist eine der häufigsten Phobien und kann die Lebensqualität der Betroffenen deutlich beeinträchtigen. Die meistgenutzte Therapiemöglichkeit ist die Expositionstherapie, bei der dem Patienten wiederholt ein furchtauslösender Stimulus dargeboten wird. Wir formulieren dieses therapeutische Setting als ein "closed-loop-System", das anhand des vorhergehenden Zustands des Patienten (gemessen mit einem "Sensor") den nächsten Stimulus wählt, um ein optimales Aktivierungsniveau beizubehalten (durch einen "Controller"). Dies ermöglicht ein besseres theoretisches Verständnis sowie die Verbesserung und Automatisierung dieser Therapiemöglichkeit.

Unsere hier vorgestellte *SpiDa Database* dokumentiert die Furchtreaktionen, die von bestimmten Stimuli ausgelöst werden. Um die Messung momentaner Furchtzustände zu verfeinern, setzen wir eine Reihe physiologischer Messinstrumente ein und verwenden maschinelles Lernen, um die ausgelöste Furcht vorherzusagen.

Fünfundfünfzig Probanden bewerteten die Furcht, die die 175 SpiDa Bilder auslösten. Durch das Trainieren von Modellen versuchen wir, diese Bewertungen anhand der verfügbaren Information vorherzusagen. Unsere Ergebnisse zeigen, dass vorrangig zwei Variablen für die Vorhersage relevant sind: Das Mittel der Bewertungen des aktuellen Stimulus durch andere Probanden sowie das Mittel der Bewertungen der vorhergehenden Stimuli durch den aktuellen Probanden. Um die 60 Prozent der Varianz der Bewertungen lassen sich mit solch einem reduzierten Modell vorhersagen.

Zusammenfassend lässt sich sagen, dass eine erfolgreiche Konzeption eines "Controller", um closed-loop Ansätze in der Therapie aber auch Forschung möglich zu machen, vor allem zweierlei benötigt: Ein gut untersuchtes Set an Stimuli, von denen bekannt ist, welche Reaktionen sie auslösen, sowie die Berücksichtigung vorhergehender Zustände des Patienten zusätzlich zum momentanen Zustand. Zur Unterstützung der Open Science Initiative werden wir sämtliches Material der *SpiDa*-Datenbank öffentlich zugänglich machen.

Acknowledgements

Science is a team sport. I try to acknowledge this team work by using the plural throughout the thesis when describing our actions. No part of this would have been possible without the help of many people: I want to thank Cindy Lor, David Steyrl and Sebastian Götzendorfer from the Scharnowski Lab for their help and support, and my supervisor Frank Scharnowski for his gentle guidance. I was never alone, and I am grateful to my fellow master students Anne Klimesch and Johannes Rother for the good collaboration.

Finally, dedicating so much time to a piece of work depends on the patience and understanding of many more people: I want to thank my family, partner and friends for their love and support.

Ethical statement

This study was approved by the ethics committee of the University of Vienna.

Table of Contents

1. Fear, Physiology & Input-Output Matching

1.1. Fear of Spiders

The adaptive value of emotions has long been recognized (Darwin, 1872). Throughout species, emotions facilitate appropriate responses to changes in the environment by activating specific brain regions and responses of the autonomous nervous system. For example, when a stimulus is perceived as threatening, the hypothalamus, and the pituitary gland consecutively, cause the emission of norepinephrine, which in turn leads to the activation of the sympathetic nervous system and facilitates fight-or-flight responses. This is accompanied by characteristic physiological changes such as an increased heart rate, pupil dilation, increased blood clotting and immunoreaction. (Critchley et al., 2013; Fendt & Fanselow, 1999; Kreibig, 2010)

What to fear in a complex environment? Appropriate emotional responses can be acquired, either by model learning or by direct experience (Olsson & Phelps, 2007, Klinnert et al., 1983). The classic case of 'Little Albert', a child conditioned to fear an originally non-threatening rabbit, illustrates the latter (Watson & Rayner, 1920). However, not all learning is equal: biological preconditions facilitate learning of emotional responses to certain stimuli (Garcia & Koelling, 1966), resulting in 'prepared learning' (Barrett & Broesch, 2012; Seligman, 197). In line with this argumentation, evolutionary psychologists claim that stimuli that make sense to be avoided in an evolutionary context, such as dangerous animals, are still being avoided today because it is easier to learn to fear them (Öhman & Mineka, 2001). In the light of signal detection theory, a 'miss' of such a stimulus is potentially penalized more than a 'false alarm', evolutionarily shaping our responses (Schechtman et al., 2010).

The specific phobia with the highest prevalence is the fear of spiders (Fredrikson et al., 1996). Spiders elicit more fear and disgust in humans than any other animal, even in non-clinical populations (Polák et al., 2019). Spider phobia occurs in approximately three percent of the population, and is over four times as prevalent in women than men (Oosterink et al., 2009; Somers et al., 2006; Sichermann, 2012).

Phobic responses to animals such as spiders can be seen as an over-reaction to this phylogenetic threat, and the patient's life can be severely restricted by the phobia when their social or professional life becomes impaired or a great stressor (WHO, 2018). Given the prevalence of such disorders, finding and optimizing therapeutic treatments is important.

1.2. Exposure therapy as a closed-loop system

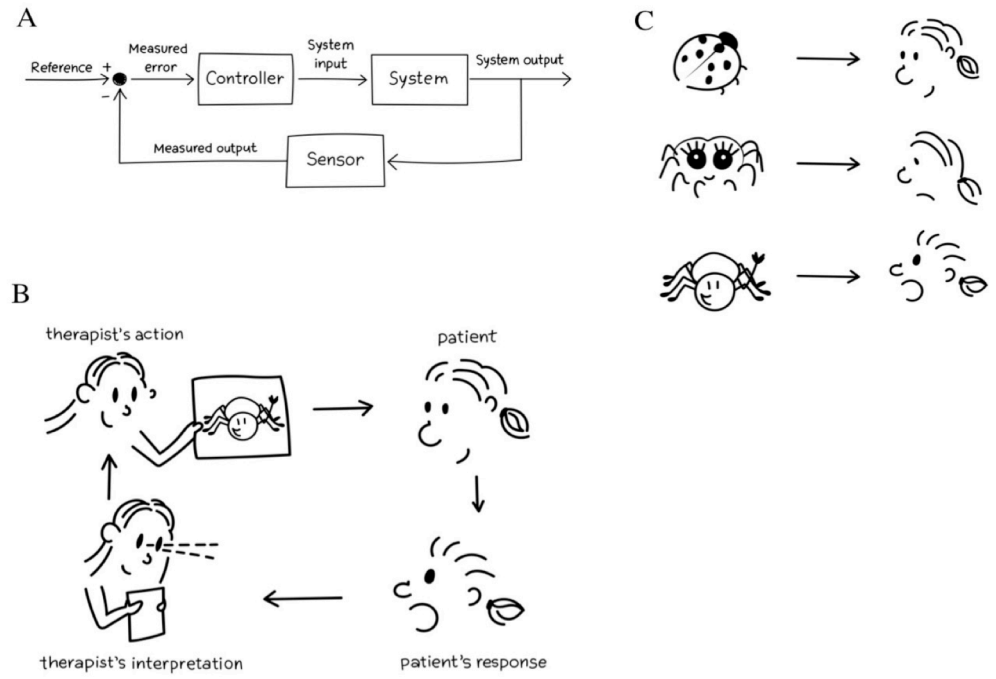
A common and successful treatment for specific phobias is exposure therapy: patients are repeatedly exposed to feared stimuli and eventually re-learn the relationship between the stimulus and the consequences (Benito & Walther, 2015, Deacon et al., 2013, Foa et al., 2006).

Although exposure therapy has repeatedly been shown to be effective in clinical trials (Öst, 1989; Öst et al., 2001**)**, vastly different approaches and procedures exist (Davis et al., 2019; Davison, 1968; Levis & Krantweiss, 2004; Parsons, & Rizzo, 2008; see Abramowitz et al., 2019); and how a therapist proceeds in practice is arguably often based on 'best practice' and subjective impressions. A possible approach to more standardized procedures would be to conceptualize the patient-therapist interaction system as a closed loop system. Such a feedback system takes into account the current state of a system, modifies it by a given input, evaluates the change and delivers the next input based on the new state (Fig.1A). Many psychological paradigms have been described in a way to fit a closed-loop system, and closed loop systems have in turn been designed to interact with psychological processes (Shanechi, 2016, 2019; Schöner, 2008). It has also been argued that the conventional open-loop approach in psychology should be advanced by 'closing the loop' of both experimental designs and explanatory models (Marken, 2009). Importantly, closing the loop can enhance the efficiency of processes (see Lorenz et al., 2016, 2019), as adaptive testing for psychological diagnostics demonstrates (Wang & Chang, 2011).

If we transferred such a closed loop to an individualized exposure therapy setting, the system input would correspond to the feared stimulus, and the system output to the patient's response. The therapist acts as a controller that compares that output to a desired reference and chooses the next stimulus based on this comparison (Fig. 1B). Crucially, the effectiveness of such sessions depends on how accurate the therapist's experience-based judgment of the patient's current state is as well as on their estimation of the response the future stimulus (system input) will elicit in the patient (system output). This estimation can be refined by input-output matching, such as examining typical reactions to different stimuli in a wide range of participants with certain characteristics (Fig. 1C). Judging a patient's level of fear is usually based on subjective ratings, verbal reports, and non-verbal signs that the therapist might notice. A possibly more objective extension to monitor and judge fear states may be to incorporate physiological measures.

Figure 1

Exposure Therapy as a Closed-Loop System



Note. (A) Schematics of a closed-loop system. Figure modified from Wikimedia Commons. (B) Formulating a therapeutic setting as a closed loop. (C) An example of input-output matching.

1.3. The physiology of fear

Psychology traditionally offers different approaches to integrating physiological responses in theories of emotion, as perhaps best illustrated by the contrasting views of the classic James-Lange and the Cannon-Bard theory of emotions (Cannon, 1927; James, 1884). Today, it is recognized that characteristic physiological arousal marks anxiety disorders (Brown & Barlow, 2002; Kogan et al, 2016; WHO, 2018), and bodily exercises such as practicing hyperventilation are a common practice in many exposure therapy settings (Abramowitz et al., 2019; Deacon et al., 2013). Thus, it seems only logical to include these physiological markers in the development and study of possible therapeutic approaches. For instance, biofeedback combined with exposure has been successfully employed in the treatment of anxiety disorders (Lin et al., 2019; Reiner, 2008; Schoenberg, & David, 2014).

Physiological changes in response to fear and anxiety have been examined by a number of studies: For example, faster breathing has repeatedly been associated with fear states (Etzel et al. 2006; Kreibig et al., 2007; Rainville et al., 2006; Van Diest et al., 2001), Van Diest et al. (2001) report an elevated pulse rate as measured in the finger upon fear

induction, and an elevation in heart rate is a classic sympathetic response that has been reported in many fear-inducing paradigms (cf. Kreibig et al., 2007, e.g. Aue et al., 2007; Palomba et al., 2000). A higher skin conductance level, response rate and magnitude of response indicate levels of physiological arousal accompanying fear (see Kreibig et al., 2007, e.g. Palomba et al, 2000), and electrodermal activity reliably indicates that a feared stimulus has been presented to participants, even if that presentation occurred subliminally (Öhman, & Soares, 1994). Increased pupil size is another indicator of sympathetic arousal (Bradley et al., 2008) and has been shown to reflect activity in certain brain areas such as the locus coeruleus, likely indicating non-luminance-mediated changes associated with sympathetic activity (Joshi et al., 2016). Changes in gazing behavior (Tolin et al., 1999) and facial muscle activity (Aue et al., 2007, 2012) have been implicated in emotional processing as well.

Even if related emotions might not always be accurately distinguishable from each other, autonomic arousal can be reliably detected by such methods (Kreibig, 2010), and advances combining machine learning and deep learning with classic theories of emotion strive to reliably detect fear levels from physiological signals (Bălan et al., 2019).

1.4. Predicting fear states

The present study aims at identifying variables, such as physiological signals, that could help to predict and estimate fear states in closed-loop exposure therapy settings. Additionally, we plan to provide input-output matching for spider stimuli by quantifying the intensity of responses to perceived threats: We present SpiDa, a database of fear-inducing spider images and the corresponding responses.

Fifty-five pre-screened, spider-fearful participants viewed and rated images of spiders, while their pupil size, skin conductance, ECG, respiration and pulse were recorded. After each picture, they were asked to rate the level of fear it induced. In this thesis, we will discuss participants' self-evaluated fear as well as their skin conductance response, changes in pupil size and respiratory activity in response to different images.

We expect that the physiological signals accurately distinguish between fear-inducing and neutral images and that we can predict fear ratings significantly better than a trivial predictor using the available signals.

Inter-individual differences contributing to these factors will be explored, and we fit machine learning models trying to predict fear ratings from all available input factors. In doing so, we examine the relative importance different variables might have for designing closed-loop settings in fear research and therapeutic settings.

In support of the open science initiative, the SpiDa stimuli, the ratings, and the physiological responses to each image will be available as open-access material. Thus, SpiDa can serve as a well-defined stimulus space for fear research and for exposure therapy settings.

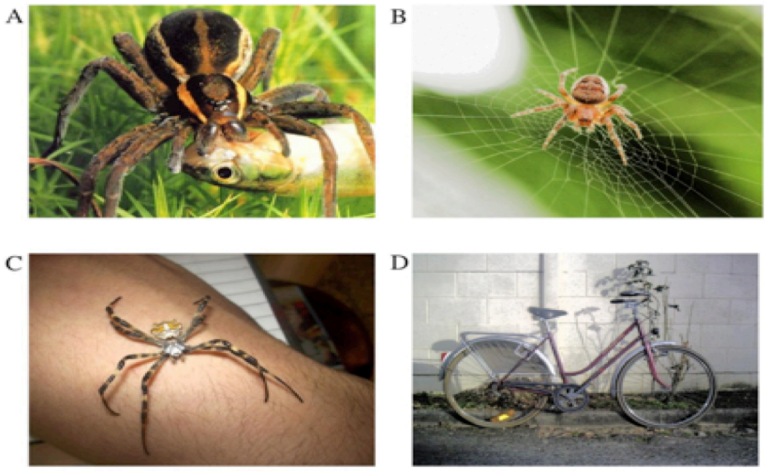
2. Material and methods

2.1. SpiDa: The Spider Images Database

We created SpiDa, a publicly available database of luminance-matched images including 175 spider pictures and 15 neutral pictures (800x600px each). Spider pictures were obtained from diverse sources of free stock photos and include pictures from the Geneva Affective Picture Database (GAPED, Dan-Glauser & Scherer, 2011). Spider images are diverse with respect to categories like perspective, distance or size of the spider. (see Table 1). Neutral pictures include objects such as a bicycle and chairs. (Figure 2)

Figure 2

Examples of SpiDa images



*Note. (*A) *Dolomedes fimbriatus* (B) *Zilla diodia*
(C) *Argiope argentata* (D) Bicycle

The mean luminance of all pictures was normalized using the Matlab (The MathWorks, Natick, USA) Toolbox SHINE color (Spectrum, Histogram, and Intensity Normalization and Equalization, Dal Ben, 2019; Willenbockel et al, 2010). Mean HSV values of the pictures are 0.5614 (SD= 0.0004189), mean LAB values 728.687 (SD= 36.863).

All pictures were first luminance matched to each other, and pictures that looked unnatural after that process were removed. The original pictures of the remaining set were then matched again to each other. This enables us and future researchers to study pupil size when using the stimuli as the procedure avoids confounders due to variance in luminance in possible future paradigms, such as changes in ERP components (Johannes, Münte, Heinze, & Mangun, 1995).

Table 1

Frequencies of different image contents in the SpiDa database.

Category	*Attributes*	*Number of pictures*
Spider in picture	no spider	9
	Spider	162
	painted spider	4
Cobweb in picture	No cobweb	118
	Cobweb	57
Number of spiders in picture	no spiders	9
	1 spider	156
	2 spiders	4
	20-60 spiders	6
Distance of spider	Not applicable	9
	close	83
	half-distant	82
	distant	1
Environment	not applicable	6
	nature	107
	civilization	46
	human contact	16
Texture	not applicable	10
	smooth	85
	hairy	80
Eyes	not applicable	9
	non-visible	95
	visible	71
Eating	not applicable	9
	not eating prey	152
	eating prey	14
Origin	not applicable	12
	exotic	105
	native in Austria	58
Subjective size	not applicable	9
	small	42
	middle	88
	large	36
Perspective	not applicable	9
	from side	58
	from top/all legs visible	108

Note. The categorization is based on subjective assessment of 3 members of the lab.

2.2. Setup and Procedure

The experiment was programed in PsychoPy 3.2.4 (Peirce, 2007). All 190 SpiDa images were presented to all participants, while physiological signals were recorded. Nineteen of those images were presented twice to each participant.

Participants completed four blocks, each starting with a relaxation phase (90 seconds) followed by 56 trials of stimulus presentation. After each block, short questionnaires assessing fear, disgust, and fatigue levels were filled in by the participants. After the final block, another relaxation phase followed.

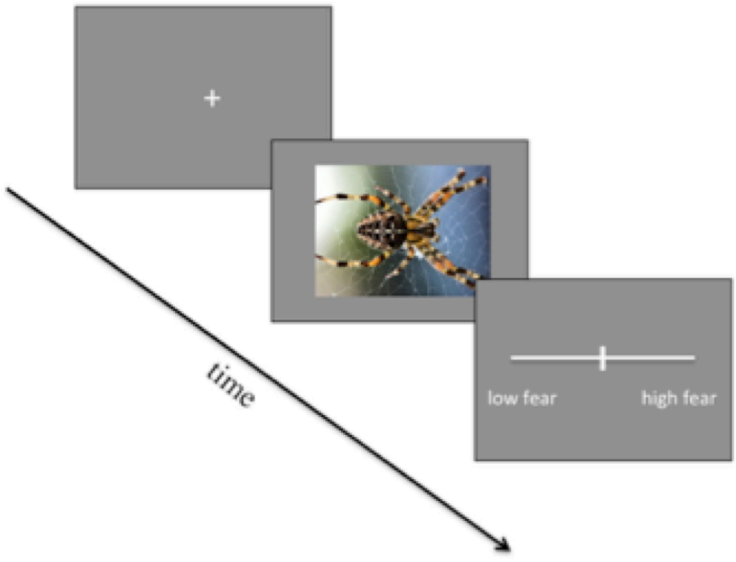
Each trial consisted of a fixation cross (random duration between 3 and 5 seconds), followed by a picture of the database (800x600px, 5 sec) and a rating phase, where participants indicated their level of fear on a continuous scale by clicking on it (Fig. 3). For the analysis, the reported position on the scale was coded between 0 (leftmost position indicating least fear) and 100 (rightmost position indicating maximum fear) in steps of 1.

Pictures were presented on a 2560x1440 pixel screen. In 85.71% of all cases a spider picture was shown, in 7.14% of the trials a neutral picture was shown instead. In the remaining 7.14% of all cases – 16 times for each participant – catch trials occurred: Instead of a picture, a short instruction was presented, asking the participants to move the mouse to either the very left or right of the scale.

A testing session consisted of briefing, the setup and sanity checks for all physiological measurements, five practice-trials with neutral pictures, the experiment (4 blocks) including three breaks, the post-questionnaires and debriefing. The whole procedure took approximately 1,5 hours per participant.

Figure 3

Schematics of a Picture-Rating Trial



2.3. Physiological Measurements

Five physiological measurements were applied simultaneously while participants completed the picture-rating-task.

Respiration: A respiration belt (BrainProducts GmbH, Gilching, Germany) was attached in the lower chest/upper abdominal area to measure breathing patterns.

Galvanic skin conductance: Electrodermal activity electrodes (Ag/AgCl, BrainProducts GmbH, Gilching, Germany) were applied to the intermediate phalanges of 2nd and 3rd digit of the inner left hand.

Pupil Dilation: A binocular, mobile eye tracker ('Pupil Core', Pupil Labs, Berlin, Germany; Kassner et al., 2004) was employed to detect the pupils of both eyes. As opposed to all other measures, the eye tracker had a non-constant sampling rate.

Electrocardiography (ECG): A single channel, 1-Lead ECG was recorded by attaching disposable ECG electrodes (Biopac, Los Angeles, USA) to the inner sides of the area just above the ankle on both legs and the back of the right hand. The right foot was used as the grounding, a lead placed with the left foot as the plus pole and the right hand as the minus pole.

Pulse: A pulse detector (Nellcor, Minneapolis, USA) was placed on the 4th digit of the left hand.

Physiological signals were amplified with a the 16-channel BrainAMP ExG MR (Brain Products GmbH, Gilching, Germany) and filtered by means of the Software BrainVision Recorder (Software version 1.22.0101, Brain Products GmbH, Gilching, Germany; upper and lower cutoff filters set at 10s and 250Hz; amplitude resolution at 0.5 μV, transmission rate ± 16.384 mV). All physiological measurements and the experimental stream were collected simultaneously and synchronized with a sampling rate of 5000 Hz. This was achieved via the lab streaming layer (LSL) system in Lab Recorder (Swartz Center for Computational Neuroscience, UCSD; Kothe et al, 2019).

2.4. Questionnaires

Prior to the experiment, participants completed three questionnaires measuring fear of spiders at home: The *Fear of Spiders Questionnaires* (FSQ, Szymanski & O'Donohue1995; German version: Rinck et al., 2002), the *Spider Phobia Questionnaire* (SPQ, Watts & Sharrock, 1984; German version: Rinck et al., 2002) and the four item screening *Spinnenangst-Screening*

(SAS, Rinck et al., 2002), which covers all relevant diagnostic criteria as specified in the DSM-IV. Additionally, participants completed the Trait-section of the State-Trait Anxiety Inventory (STAI, Spielberger et al., 1983; German version: Laux et al., 1981; Grimm, 2009).

Immediately after the experiment, participants again completed the FSQ and SAS questionnaire. During the experiment, participants filled in four identical questionnaires assessing their current degree of fear, disgust, physical excitement, boredom and exhaustion, each on a scale of 0 to 10.

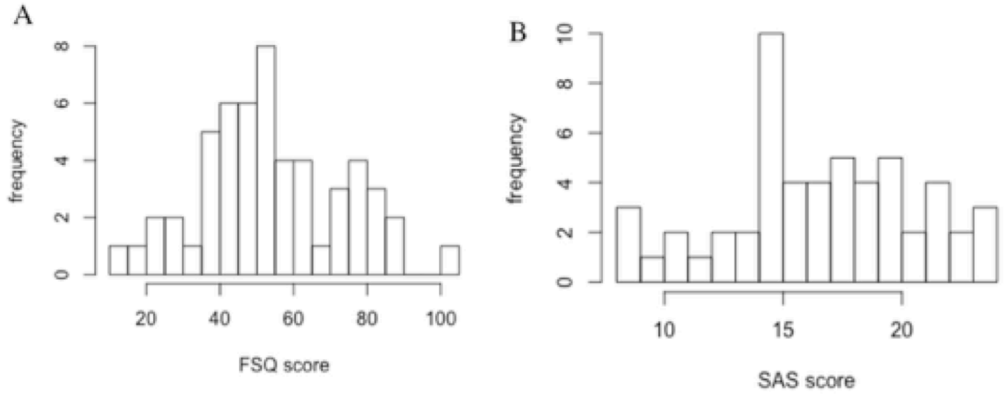
2.5. Participants

A subclinical sample of *N*= 55 spider-fearful individuals aged 18 to 30 years (mean age = 21.61 years, *SD*= 3 years) took part in the experiment. Subjects received either course credits or money (20,- euro) for their participation.

They self-reportedly had fear of spiders and on average had an FSQ-score of 54.42 (*SD*= 19.39, see Fig.4) and an average SAS of 17.04 (*SD*= 4.04) before the experiment. Of the 55 participants, 53 were classified as spider-fearful and none as non-anxious according to the screening results. This classification is based on Rinck & Becker (2007), who classify individuals with an FSQ above or equal to 24 as *spider-fearful* and those with a score equal to or lower than 8 as *non-anxious*. For the SAS, they describe participants with a score above 15 as *high fear* and under 5 as *low fear*, resulting in 33 high fear and no low fear participants (22 participants were close to being classified as high fear, see Fig. 4; Rinck & Becker, 2007).

Figure 4

Histogram of Participants' FSQ and SAS Scores (pre-test).



2.6. Analysis

Trimming and Deconvolution of Physiological Measurements

Trimming of the data consisted of removing those parts of the recording where participants were not exposed to pictures. In addition, since the eye-tracking device did not acquire pupil diameter with a fixed sampling rate, pupil data points were interpolated and re-sampled to a 250 Hz sampling rate in Matlab 9.7., and only the left eye was used.

For each picture presented to each participant, we extracted a corresponding value (β-value) of each physiological measurement. To do so, we used deconvolution with the Least Squares- Separate Approach (Mumford et al., 2012). For each trial, this approach models a separate GLM with the signal during presentation of that image as a first predictor against a nuisance regressor created from all other trials of that participant (Mumford et al, 2012). This enables a more precise estimation of the effect of each trial relative to all other trials. The extraction of β-values was conducted using the Matlab Toolbox PsPm 4.2. (Psycho-Physiological Modeling, available at http://bachlab.org/pspm). The β-values obtained were used in all subsequent statistical analysis.

Statistical Analysis

We employed Bayesian estimation models for both independent and paired samples when comparing two groups and Bayesian inference of Pearson correlations. For these tests, we reported Bayes factors (*BF*, H_0 against H_1) rather than p-values, since they are less frequently misinterpreted and can be interpreted directly as the amount evidence of a hypothesis compared to another (Cox, 2006; Greenland et al., 2016; Held & Ott, 2018). We chose objective reference priors for group comparisons (Berger & Bernardo, 1989) and a uniform prior distribution for correlations. Conventional measures of effect size were reported.

To predict self-reported fear, we employed a linear (least absolute shrinkage and selection operator [LASSO], Tibshirani, 1996), and a non-linear machine learning model (Extremely Randomized Trees [ET], Geurts et al., 2006).

We used nested cross validation (90/10, 100 iterations each) and controlled for subject clustering (stratified cross-validation). Input variables were participant characteristics (such as mean disgust rating or the FSQ-score), picture characteristics (such as the size or the texture of the spider), and physiological signals. All 16 input variables are displayed in Figure 7, where permutation feature importance is depicted for each input as the proportional loss of overall explained variance if the input is replaced by a random (non-informative) array of that variable.

All analyses were conducted in Python 3.7.7. (Scikit-learn 0.22.2., Pedregosa et al., 2011), IBM SPSS Statistics (version 25.0) and R (R Core Team, 2017).

3. Results

3.1. Exclusions

Catch Trials

We rated a catch trial as successfully completed if the rating was within the leftmost 5 % of the scale and within the rightmost 5% of the scale when asked to move the cursor to the left or right respectively. On average, participants responded correctly in 98% of the trials (SD= 5%). One person was excluded for not reacting appropriately in at least 80% of all Catch trials.

Quality of Data

Two participants were removed from all analyses because of poor quality of the physiological signals.

3.2. Questionnaire data

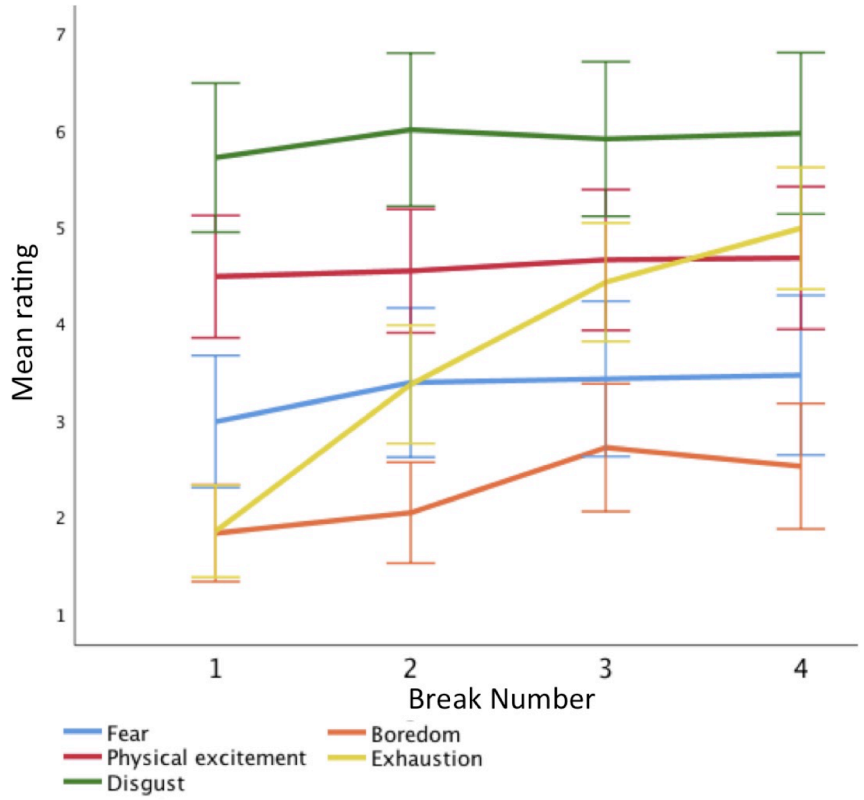
Fear and Disgust

As depicted in figure 5, self-reported levels of fear, disgust, physical excitement and boredom remained fairly stable throughout the experiment, whereas ‘exhaustion’ increased notably. The break questionnaires further confirm that disgust is an important factor in spider phobia, since overall, participants reported higher levels of disgust than fear (see Fig. 5).

Mean ratings of the fear induced by the SpiDa images (ratings) per participant highly correlated with the mean self-reported level of fear reported in the break questionnaire with R= .614 and an $BF < 0.001$ (N=52). The mean disgust ratings on the break questionnaire correlated with the mean fear ratings of SpiDa images with Pearson’s R= .366 and an BF of .270, thus explaining 24.30 percentage points less of the variance than the indicated fear. Additionally, the Bayes factors imply that the existence of a connection between ratings and fear is much more likely than none, which is not as pronounced for the connection between ratings and disgust.

Figure 5

Levels of Self-Reported Feelings



Note. Mean self-reported levels of fear (blue), disgust (green), physical excitement (red), boredom (orange) and exhaustion (yellow) over the course of the experiment, as measured during the breaks in between the blocks. 95% CI depicted.

Pre and Post: Fear of Spiders Questionnaire (FSQ) and Spinnen Angst Screening (SAS)

Both the FSQ and the SAS were used for screening several days before the testing and completed again right after the testing session. Interestingly, there were numerical differences between the two points in time: The SAS score decreased with a mean difference of 2.21 (*SD*= 3.076, *BF*> 0.001), and the FSQ score decreased with a mean difference of 2.08 (*SD*= 14.715). Nevertheless there is no evidence in favour of group differences (*BF*= 5.559).

For both questionnaires, the scores obtained after the testing sessions explained more of the variance of the SpiDa ratings, and the Bayes factors showed a higher probability for an association of the ratings with the scores obtained after the session than with those obtained during screening (FSQpost: R= .629, *BF*<0.001, FSQ_{pre}: R= .270, *BF*= 1.437; SAS_{post}: R= .506, *BF*= 0.006; SAS_{pre}: R= .273, *BF*= 1.361; N=52).

3.3. Rating data

Repeated Presentation of Pictures

To assess repetition effects, 19 spider images were presented twice to the participants. Ratings of these images differed between the first and second presentation, however, the differences were small (N= 1026, mean difference= 3.21, BF<0.001; $mean_1$= 53.32, SD_1=29.52); $mean_2$= 50.11, SD_1=29.84).

Proof of Principle: Neutral Pictures versus Spiders

As expected, neutral pictures of the SpiDa were rated as less fear inducing than pictures containing spiders or cobwebs (BF < 0.001); $mean_{neutral}$ = 2.55, $SD_{neutral}$ = 3.737, $N_{neutral}$ = 832; $mean_{spider}$ = 55.30, SD_{spider} = 13.94, N_{spider} = 9984).

3.4. Physiological data

Proof of Principle: Neutral Pictures versus Spiders

The mean skin conductance β-values were indeed lower for neutral pictures than spider pictures (BF = 0.002; $mean_{neutral}$ = 5.2069E-4, $SD_{neutral}$ = 3.08799E-3, $N_{neutral}$ = 832; $mean_{spider}$ = 5.03540E-5, SD_{spider} = 3.60550E-3, N_{spider} = 9984). Respiration values, too, were lower for neutral pictures compared to spider pictures (BF = 0.001; $mean_{neutral}$ = 1.22829E-2, $SD_{neutral}$ = 3.00662E-2, $N_{neutral}$ = 832; $mean_{spider}$ = 1.66332E-2, SD_{spider} = 2.64964E-2, N_{spider} = 9984).

Values for pupil dilation were numerically higher in the neutral condition than for spider-images, however, the Bayes factors suggest that it is unlikely that these data actually reflect group differences (BF = 29.343; $mean_{neutral}$ = 5.94398E-4, $SD_{neutral}$ = 1.58518E-2, $N_{neutral}$ = 832; $mean_{spider}$ = 3.11166E-4, SD_{spider} = 1.38533E-2, N_{spider} = 9984). Thus, as opposed to skin conductance and respiration, the values for pupil dilation as obtained by this analysis do not seem to accurately reflect the fear induced by spider images.

3.5. Predicting fear ratings from physiology, picture characteristics and participant traits

We attempted to predict participants' fear ratings from a range of inputs characteristic for each participant (such as previous ratings and physiological response) and for the picture (such as the number of spiders). To do so, we use a linear (LASSO) and a non-linear model (extremely randomized trees).

Our most extensive model takes into account 16 input variables and 8774 trials. On average, we were able to predict 49 percent of the variance if a linear model is used (*SD*=0.12; median R^2= 0.48) (Fig. 6A). The non-linear models predicted on average 0.46 percent of the variance (SD=0.14; median R^2= 0.44) (Fig .6B). The mean absolute error for the linear model is 12.88 (root of mean squared error= 16.4) and 13.59 for the non-linear model (root of mean squared error= 17.23), thus, predictions can be made with ± 13 points precision on the rating scale from 0 to 100. Both models perform significantly better than a trivial predictor (always predicting the mean of all ratings) at a 95% CI ($p<0.001$).

Although the linear and non-linear models both predict a similar amount of the variance of the ratings, not all features were taken into account in the same way. Most notably, disgust ratings in the breaks do have predictive power in the non-linear models, but not the linear models. The same applies to the FSQ score obtained during the screening and the SAS score obtained after the testing session. Figure 7 shows the predictive value of each input factor, depicted as the proportional reduction of the explained variance if that feature is replaced by a random array of that feature for the linear (A) and non-linear (B) models.

For both models, the most important predictors were how the participant had rated the previous pictures on average, how the picture had been rated by other participants, and the participant's FSQ score obtained right after the experiment (Fig. 7).

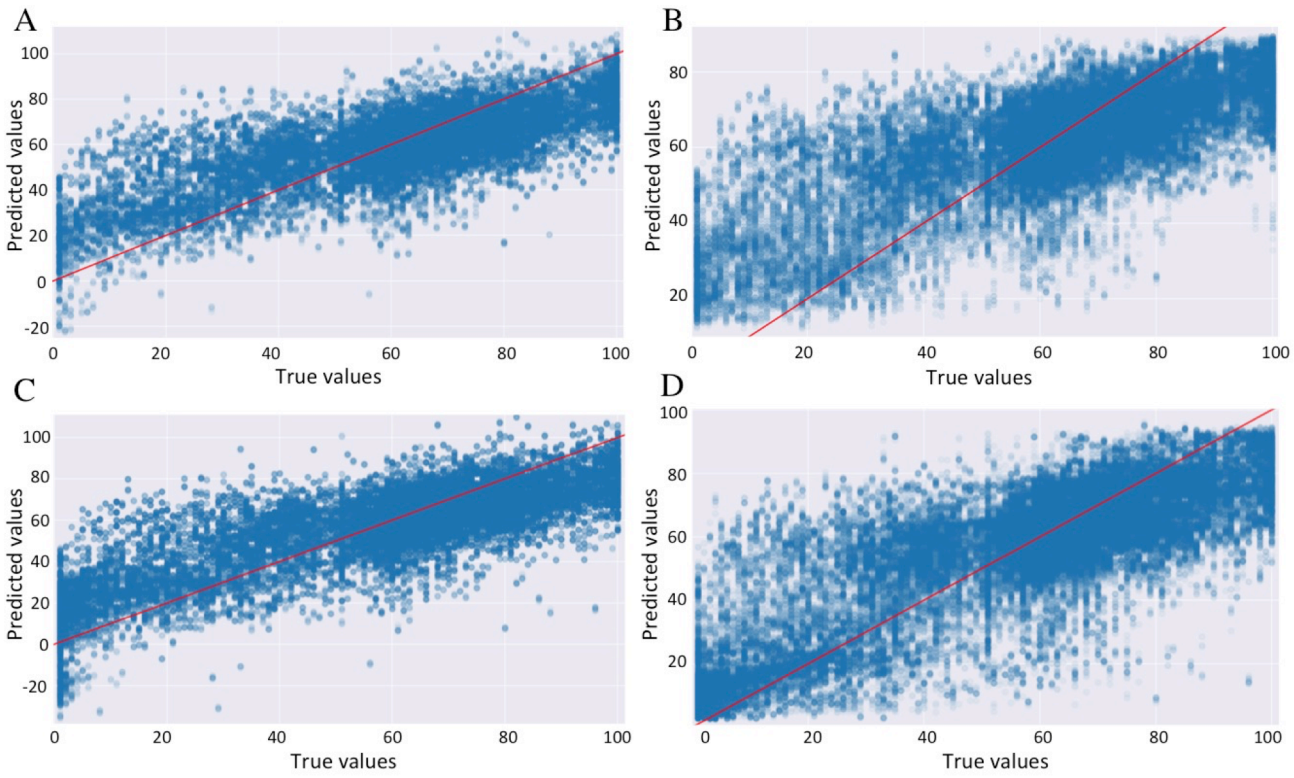
Next, we fit a minimal model that only takes into account two values that have been shown to be most influential in the more extensive model: The mean of all the ratings a participant has completed until this picture and how the current picture has been rated by all other participants. Less exclusions due to missing data allowed for 9741 trials to be included.

Simple linear models with these two input factors explained on average 60 percent of the variance (SD=0.08; median R^2= 0.61; mean absolute error= 12.93, root of mean squared error= 16.74). The non-linear models explained on average 0.62 percent of the variance (SD=0.08; median R^2= 0.61; mean absolute error= 12.20, root of mean squared error= 16.05).

Again, both models performed significantly better than a trivial predictor ($p<0.001$). Figure 6C (linear) and D (non-linear) shows the model fit for these reduced models.

Figure 6

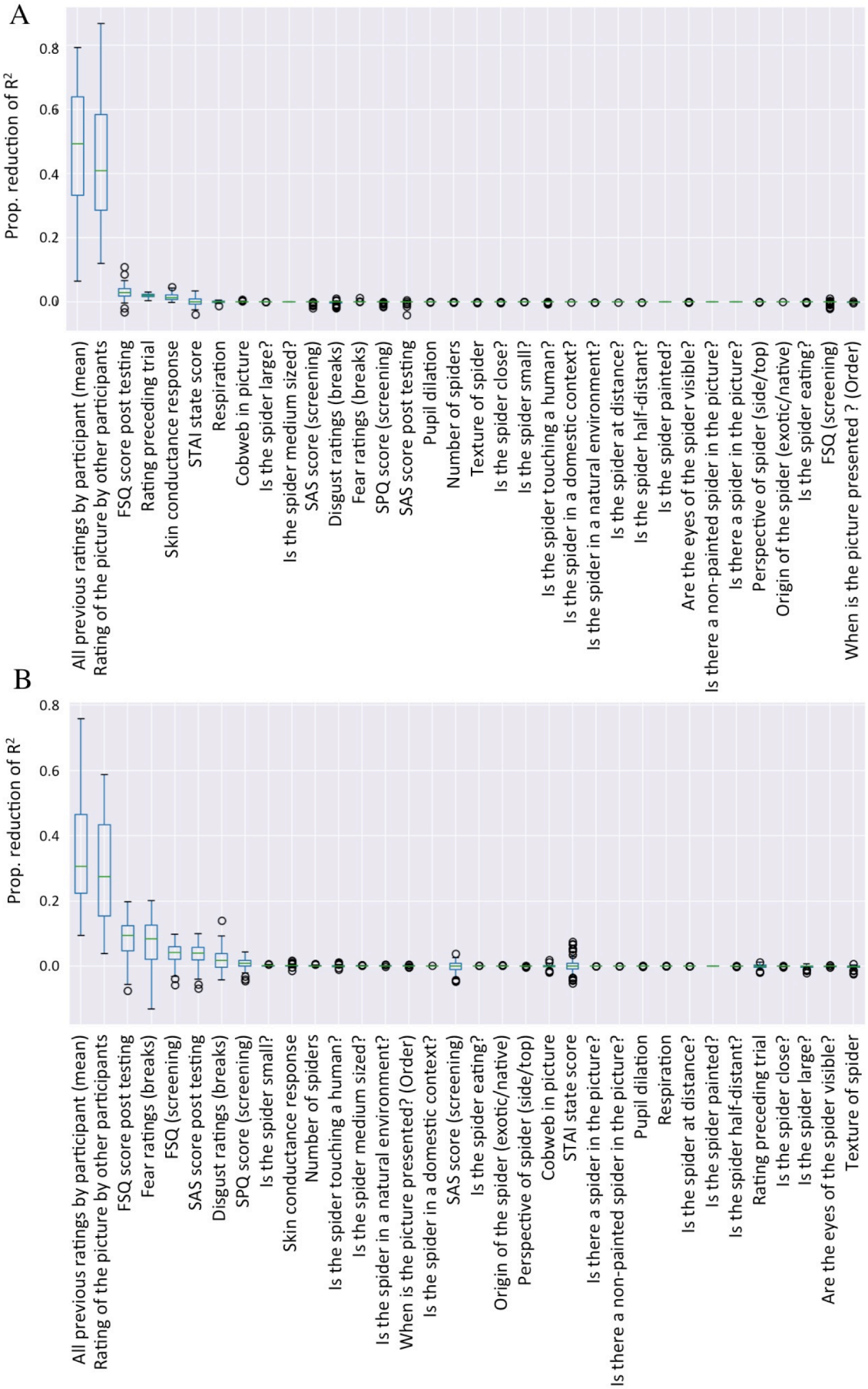
Model Fit



Note. Model fit shown by plotting the regressor predicted values against the given true values for (A) the LASSO regression using all input variables, (B) extremely randomized trees using all input variables, (C) the LASSO Regression using just two input variables, and (D) extremely randomized trees using just two input variables: The average of the previous ratings for the participant and the average for the current stimulus from other participants.

Figure 7

Input Feature Importance



Note. Permutation feature importance of each input variable in the extensive linear (A) and non-linear (B) model

4. Discussion

The present study set out to explore the role of physiological measurements in the assessment of fear and to find variables that are well suited to design controllers in closed-loop approaches for exposure therapy and fear research (see Fig. 1A). To achieve this goal, we created a new SpiDa database of luminance-matched spider and neutral pictures that were evaluated by 52 participants while physiological signals were recorded and standardized psychological questionnaires were administered at different points in time.

In predicting the fear induced by a particular picture, we took into account physiological signals at the time of presentation, properties of the current picture (such as the size of the spider) and participant traits (such as questionnaire scores). Importantly, the most useful variables in making successful predictions were how the current image had been rated by other participants and how the participant had rated the previous images. A simple model with these input variables trained on other participants can on average predict 60 percent of the variance of how fearsome an image will be rated by a new participant (Fig. 6 C, D). All other variables only marginally contributed to the explained variance (see Fig. 7). Although containing little predictive value, physiological signals such as skin conductance response differed between neutral and spider images (3.4.) and also questionnaires scores correlated with the fear ratings (3.2.). In line with the limited predictive potential of physiological signals, Aue et al. (2012) reported that electrodermal activity may only reflect very high levels of fear, and several studies have found no meaningful changes in physiological signals such as respiration (Sarlo et al., 2002). Nevertheless, an overwhelming amount of studies documents characteristic physiological changes in response to emotional processing (cf. Kreibig et al., 2007).

Notably, how other participants had rated the current input was a very important predictor of a new participant's response, even though objective characteristics of that picture (such as the number or size of spiders) had no predictive power and did not seem to capture the essentials of the current input.

Whilst many variables measuring the current state of the participants, such as respiration, did not contribute much to determining that current state, the good predictive value of a participant's previous ratings emphasizes that taking previous states into account can help to refine a current measurement. This has been long recognized by other disciplines, and many technical devices operate on recursive functions (cf. Kalman filters, Welch &

Bishop, 1995). Psychology, too, might profit from shifting its viewpoint when measuring psychological states. Many psychological domains such as learning, social interactions, perception are in fact dynamic closed-loop systems. Incorporating not only current, but also previous states is a first step in taking such dynamics seriously.

Our results, combined with further research, may be particularly useful for developing evidence-based, individualized procedures in exposure therapy and potential low-barrier automatized therapeutic devices for affected individuals. This is not a novel approach: Computerized and even self-administered exposure therapy has been successfully implemented before (Dewis et al., 2001; Matthews et al., 2010). Recent studies aimed at computerizing exposure therapy using physiological signals (Watson et al., 2019), and Zilverstand et al. (2015) employed closed-loop neurofeedback to regulate spider phobia. More easily accessible mobile applications are being developed to help with psychological problems such as anxiety and phobias (Bakker et al., 2016; Kertz et al., 2017). However, most of these applications are far from being evidence-based (Kertz et al., 2017).

Interpersonal differences in fear of contamination may be crucial predictors for the development of spider phobia (De Jong et al., 2002). Like fear, disgust is an evolutionary important basic emotion that can be transmitted via different modalities (Stefańczyk & Oleszkiewicz, 2020), and has been found to play an important role in spider avoidance (Woody et al., 2005; see Fig. 5 for disgust in our sample). In our analysis, disgust has been found to have some predictive power with regard to how fearsome the pictures are perceived. However, this was only the case for non-linear models (Fig.7), indicating a complex interplay between disgust and fear.

Similarly, two questionnaires measuring fear of spiders had some predictive power only in the nonlinear model, suggesting that the relationship between these self-assessment instruments and actual responses is not necessarily captured with linear models.

Our sample consisted mostly of female Viennese students. While this facilitates the predictions for our models, it limits the generalization of our results to other samples. Furthermore, our spider stimuli do not equally well cover the entire fear spectrum (i.e. there are fewer stimuli being rated as not or very fear provoking). Adding stimuli from these fear intensities to the database might enhance its use for practical applications. Both limitations can be addressed by online rating experiments in larger samples. Collecting a sufficiently

large number of stimuli that score high/low on the fear scale and vice versa on the disgust scale might also help to disentangle the role of fear and disgust in spider phobia.

In conclusion, this study identifies variables that are important in predicting future fear states, and represents a first step towards evidence-based practices and automated exposure therapy. The fact that information available from rating data seems to be most important in predicting future states is particularly promising for the development of easily implementable tools.

The SpiDa images and the corresponding values will be made openly accessible to researchers and practitioners: Since the ratings of an image by other participants were one of the most important predictors of a participant's response, this well-defined stimulus space is a valuable tool for future studies on fear responses or when investigating and implementing closed-loop approaches in exposure therapy.

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