

SUPPLEMENTARY MATERIAL

Characterizing Physiological Responses to Fear, Frustration, and Insight in Virtual Reality

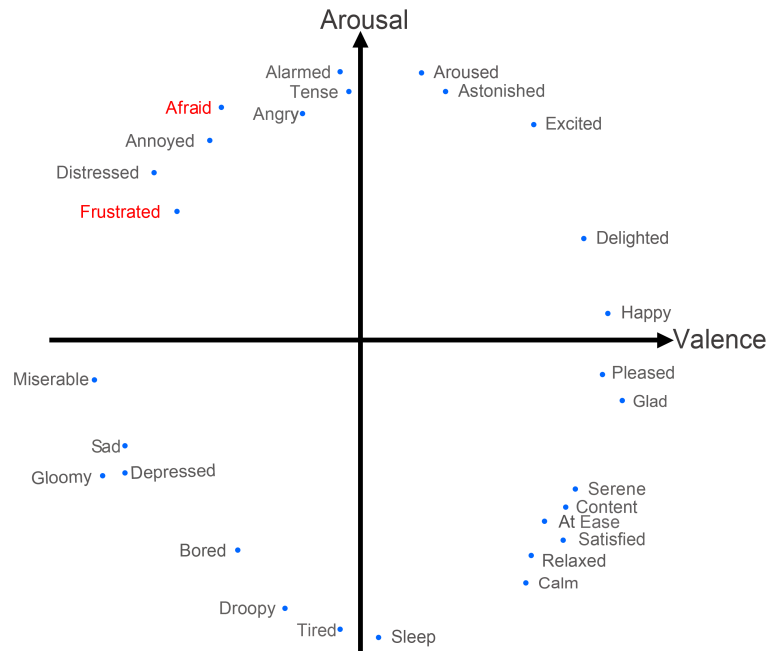


Fig. A1: Russell's circumplex model of affect [51]. *Afraid* and *frustrated* are situated in the same emotional space.

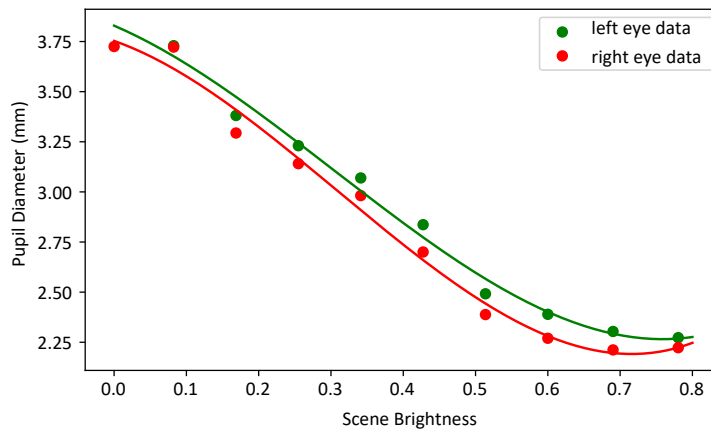


Fig. A2: Effect of the scene brightness on the pupil diameter for one participant. The scene brightness did not exceed .78 in our study. We assessed participants' responses to brightness before the experiment to later compensate for their behavior in our analysis.

Baseline vs. Fear			
Modality	Feature	<i>r</i>	<i>p</i> Δ
PPG	bpm	.21	.04 * ↑
	sdnn	.21	.1 + ↓
	sdsd	.1	.6 ↓
	rmssd	.16	.1 + ↓
	pnn50	.02	.67 ↓
	hr mad	.02	.59 ↓
EDA	SCR mean peaks amplitude	.33	.02 * ↑
	SCR max peaks amplitude	.36	.02 * ↑
	SCR std peaks amplitude	.36	.02 * ↑
Eyes	No of blinks	.14	.54 ↓
	mean pupil diameter	.22	.02 * ↓
	min pupil diameter	.23	.09 + ↓
	max pupil diameter	.61	.0001 *** ↑
	std pupil diameter	.23	.04 * ↑
Resp	respiration rate	.56	< 0.0001 **** ↑

Baseline vs. Frustration			
Modality	Feature	<i>r</i>	<i>p</i> Δ
PPG	bpm	.05	.01 ** ↑
	sdnn	.21	.004 ** ↓
	sdsd	.08	.2 ↓
	rmssd	.23	.003 ** ↓
	sd1	.2	.01 * ↓
	sd1.sd2	.17	.1 + ↓
EDA	SCR N peaks	.27	.1 + ↑
	SCR mean peaks amplitude	.08	.35 ↑
	SCR max peaks amplitude	.13	.1 + ↑
	SCR std peaks amplitude	.2	.05 * ↑
	SCR peaks mean rise time	.6	.6 ↓
	SCR peaks max rise time	.1	.4 ↓
Eyes	SCR mean recovery time	.12	.2 ↓
	No of blinks	.34	.02 * ↓
	mean pupil diameter	.35	.0002 *** ↑
	min pupil diameter	.4	.0001 *** ↑
	max pupil diameter	.23	.007 ** ↑
std pupil diameter	.54	< 0.0001 **** ↓	
Resp	respiration rate	.64	< 0.0001 **** ↑

Baseline vs. Insight			
Modality	Feature	<i>r</i>	<i>p</i> Δ
PPG	bpm	.07	.04 * ↑
	sdnn	.04	.6 ↑
	sdsd	.16	.4 ↓
	pnn20	.1	.58 ↑
	pnn50	.1	.75 ↑
	hr mad	.1	.38 ↑
EDA	SCR mean peaks amplitude	.13	.3 ↑
	SCR max peaks amplitude	.15	.2 ↑
	SCR std peaks amplitude	.19	.35 ↑
	SCR max recovery time	.11	.46 ↑
Eyes	mean pupil diameter	.53	.0002 *** ↑
	min pupil diameter	.23	.2 ↓
	max pupil diameter	.62	< 0.0001 **** ↑
	std pupil diameter	.61	< 0.0001 **** ↑
Resp	respiration rate	.42	.0007 *** ↑

Table A1: Effect of the states (fear, frustration, insight) on the physiological signals against the baseline. Δ indicates the relation from the baseline to the state. Only features with $p \leq .1$ or $r \geq .1$ are presented. Significances: $+p \leq .1$, $*p \leq .05$, $**p \leq .01$, $***p \leq .001$, $****p \leq .0001$.

Fear vs. Frustration			
Modality	Feature	<i>r</i>	<i>p</i> Δ
PPG	bpm	.16	0.6 ↑
	rmssd	.05	.9 ↓
EDA	SCR N peaks	.22	.6 ↑
	SCR mean peaks amplitude	.1	.64 ↑
	SCR max peaks amplitude	.1	.4 ↓
	SCR peaks std rise time	.12	.3 ↑
	SCR mean recovery time	.1	.37 ↓
	SCR std recovery time	.1	.41 ↑
Eyes	No of blinks	.36	.05 * ↓
	mean pupil diameter	.41	.001 ** ↑
	min pupil diameter	.59	.0002 *** ↑
	max pupil diameter	.63	.0002 *** ↓
	std pupil diameter	.7	.0002 *** ↓
Resp	respiration rate	.26	.17 ↑

Fear—Vertigo vs. Fear—Horror			
Modality	Feature	<i>r</i>	<i>p</i> Δ
PPG	bpm	.22	.21 ↑
	rmssd	.23	.37 ↓
	pnn20	.34	.28 ↓
	sd1	.25	.24 ↑
	sd1.sd2	.3	.08 + ↓
EDA	SCR mean peaks amplitude	.13	.58 ↓
	SCR max peaks amplitude	.12	.64 ↑
	SCR peaks std rise time	.1	.52 ↑
Eyes	No of blinks	.35	.05 * ↓
	mean pupil diameter	.29	.08 + ↓
	min pupil diameter	.45	.02 * ↓
	max pupil diameter	.72	.0002 *** ↑
	std pupil diameter	.21	.03 * ↑
Resp	respiration rate	.15	.43 ↓

Table A2: Difference between fear and frustration and difference between fear in a horror game and fear in a vertigo environment. Δ indicates the relation from the first state to the second state indicated in the header. Only features with $p \leq .1$ or $r \geq .1$ are presented. Significances: $+p \leq .1$, $*p \leq .05$, $**p \leq .01$, $***p \leq .001$, $****p \leq .0001$.

Modality	Fear—Horror			Fear—Vertigo			Fear			Frustration			Insight		
	<i>log</i>	<i>lsvc</i>	<i>rf</i>	<i>log</i>	<i>lsvc</i>	<i>rf</i>	<i>log</i>	<i>lsvc</i>	<i>rf</i>	<i>log</i>	<i>lsvc</i>	<i>rf</i>	<i>log</i>	<i>lsvc</i>	<i>rf</i>
ppg	.464	.630	.488	.664	.561	.669	.528	.587	.535	.587	.586	.568	.463	.530	.629
eda	.591	.568	.568	.639	.556	.667	.617	.599	.582	.527	.510	.535	.604	.679	.685
eyes	.625	.636	.670	.619	.595	.571	.559	.508	.495	.705	.722	.707	.505	.509	.653
resp	.542	.444	.444	.472	.444	.389	.524	.473	.518	.605	.594	.634	.553	.524	.620
ppg, eda	.687	.691	.430	.517	.522	.489	.638	.651	.559	.576	.571	.526	.651	.614	.743
ppg, eyes	.712	.656	.645	.539	.572	.553	.529	.470	.451	.696	.708	.652	.575	.553	.699
ppg, resp	.472	.542	.532	.628	.608	.731	.575	.648	.540	.621	.629	.570	.519	.509	.656
eda, eyes	.693	.659	.591	.694	.667	.528	.560	.583	.573	.665	.676	.648	.589	.623	.647
eda, resp	.597	.569	.486	.611	.556	.472	.635	.586	.597	.556	.545	.611	.583	.549	.721
eyes, resp	.611	.583	.542	.556	.528	.361	.488	.440	.469	.734	.744	.702	.540	.481	.659
ppg, eda, eyes	.688	.687	.574	.750	.667	.642	.563	.559	.485	.669	.664	.599	.640	.595	.748
ppg, eda, resp	.500	.667	.417	.517	.489	.453	.644	.656	.496	.587	.582	.562	.662	.649	.702
ppg, eyes, resp	.532	.514	.699	.544	.539	.567	.488	.569	.586	.738	.759	.678	.525	.537	.669
eda, eyes, resp	.625	.583	.514	.667	.611	.583	.610	.555	.506	.696	.675	.658	.596	.603	.709
ppg, eda, eyes, resp	.569	.528	.495	.694	.667	.544	.542	.651	.451	.726	.722	.637	.628	.581	.748

Table A3: Average F_1 scores were obtained by performing a leave-one-out participants evaluation for each model. The data varies between the different models as we only considered data with a SUDS score ≥ 40 and a frustration score ≥ 3 . Noisy physiological signal portions were also excluded. Best performances per combination of sensors for each state are highlighted in blue, and best classifiers for each state are bolded. We used the following algorithms: *log* = Logistic Regression, *lsvc* = Linear Support Vector Classifier, *rf* = Random Forest.