Title

The use of stimulus perception to account for variability in skin conductance responses to interoceptive stimuli.

Running head

Intensity perception and the SCR

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Abstract

Activity of the electrodermal response system is customarily expressed in relation to physical stimulus properties and not to perceived features. In situations where the delivery of physically identical stimuli can be challenging, such as in interoception research, this variability might pose a challenge for contemporary SCR analyses. Therefore, we investigated the extent to which activity in the electrodermal response system triggered by the delivery of interoceptive stimuli is better predicted by perceived intensity rather than physical input. For this purpose, we re-analyzed data from the baseline phase of a previous study (n=60) [Zaman et al. (2017)] in which skin conductance responses to innocuous esophageal stimulations of high and low intensities were recorded in addition to categorizations based on their perceived intensity (high or low). Using both peak scoring and model inversion methods, we found that the inclusion of stimulus perception as a predictor of the magnitude of the skin conductance response increased model fit. These findings suggest that the inclusion of perception is a promising avenue to better model variability in psychophysiological responses to interoceptive stimuli.

Keywords: skin conductance response; perception; physical intensity; categorization

Introduction

The skin conductance response (SCR) is one of the most frequently adopted psychophysiological measures of arousal in a wide range of scientific domains, including but not limited to psychology and psychiatry (Dawson, Schell, & Filion, 2007). This electrodermal response reflects the activity of the sympathetic branch of the autonomic nervous system that controls the activation of sweat glands, which in turn affects the conductive capacity of the skin (Dawson et al., 2007). The SCR is often observed following the presentation of novel, unexpected, significant or aversive stimuli. It has been well established that the magnitude of the SCR increases with stimulus salience (Barry & Furedy, 1993; Jackson, 1974; Turpin, Schaefer, & Boucsein, 1999; Turpin & Siddle, 1979; Vossel & Zimmer, 1992), which is typically operationalized as physical stimulus intensity. However, few studies focused on whether skin conductance responses can be best modeled as a function of the physically presented stimulus intensity, the perceived intensity or a combination of both.

Given the inferential and stochastic nature of perception, a one-to-one correspondence between physical and perceived intensity is often lacking (Kersten, Mamassian, & Yuille, 2004). Hence, SCR models where both stimulus features and perception are used as predictors might be superior compared to the traditional models that only predict SCR based on stimulus features. For example, variations in SCR inherent to repeated stimulus presentations could be linked to fluctuations in stimulus perception. Especially, in contexts where perception is expected to strongly deviate from physical input or sensory domains that are inherently characterized by high variability and low precision (such as interoception), the inclusion of perception in SCR analyses might improve model fit.

Research has demonstrated that, generally, perceived stimuli elicit larger SCRs compared to subliminal stimuli, suggesting that perception may influence the magnitude of the SCR [although SCRs to subliminal stimuli have been reported (Knight, Nguyen, & Bandettini, 2003; Olsson & Phelps, 2004)]. In addition, the influence of expectations and learning on the SCR illustrate its sensitivity to higher order processes (Critchley, 2002). In a recent study, Mischkowski and colleagues (2018) explored the relationship between physical stimulus intensity, perception and strength of the SCR using mediation analyses. In their study, a range of noxious and innocuous heat stimuli was presented, and their perceived intensity was assessed using intensity ratings. The authors found a strong relationship between intensity ratings and the magnitude of the SCR. However, apart from this preliminary work, the relationship between perception and SCR remains unclear.

The aim of the current study was therefore to assess the relative contribution of physical and perceived stimulus intensity towards SCR magnitude within an interoceptive modality. To this end, we re-analyzed data of 60 participants from a previous study (Zaman et al., 2017) that explored perceptual

decision-making in a context of visceral fear learning. During the baseline phase, SCRs to repeated, unannounced presentations of innocuous esophageal balloon distensions of a high (S_H) and low (S_L) physical intensity ($13.39 \pm .55$ (SE) and $10.94 \pm .42$ PSI on average, respectively) were recorded. Further, perceptual categorizations (high vs low) were assessed immediately after stimulus presentation. We expected that a statistical model that included perceptual judgments would predict the amplitude of the SCR significantly better compared to a model that solely focused on the effect of physical intensity.

Materials and Methods

The complete material and methods section was reported elsewhere (Zaman et al., 2017), but a summary of the information that is relevant for the analyses in the present paper is provided below.

Participants

Sixty participants completed the entire experiment [33 female, 27 male; mean age: 21.4 (SD = 2.2)], which was approved by the Medical Ethical Committee of the University Hospitals Leuven prior to the start of participant recruitment.

Esophageal stimulation

A 2.7mm pediatric feeding tube (TR-2008, Pennine©) with a deflated custom-made medical balloon (25mm, Medasil©) attached to the end was inserted transnasally, with the balloon placed in the distal, autonomically innervated part of the esophagus, approximately 35cm from the nostril. The extracorporeal part of the tube was draped over the ear and attached with adhesive tape to prevent it from moving, similar to previous research (Ceunen et al., 2016; Weltens et al., 2013; Zaman et al., 2016). A custom-made inflation pump (Medical Physics department, Salford Royal NHS Foundation Trust) with a digital display was used to inflate and deflate the balloons. The inflation time was set at 250ms and the dwell time at 0s, therefore the esophageal stimuli had a total duration of approximately 250ms (inflation + deflation time) (Fig. 1). After insertion of the esophageal balloon, perceptual thresholds were determined using the Ascending Methods of Limits approach (Yarnitsky, Sprecher, Zaslansky, & Hemli, 1995). For this purpose, participants rated the intensity of the balloon distensions on a visual analog scale (VAS, 0 = not intense, 10 = very intense), and were instructed that these stimuli should not be painful. Pressures corresponding to VAS ratings of 4 and 6 were used. At the start of the experiment, an average pressure of 10.94 PSI (SE = .42) was used for the low-intensity stimulus (S_L) and a pressure of 13.39 (SE = .55) for the high-intensity stimulus (S_H). Balloon pressures were recalibrated in between the experimental blocks (Block 2: S_L = 12.76 (SE = .55), S_H = 15.48 (SE = .60) Block 3; S_L = 14.52 (SE = .63), S_H = 17.00 (SE = .70). In 90% of the participants, higher stimulation pressures were used for both stimuli across the experiment (block 3 vs. block 1). In 3.33% balloon pressure was not

adjusted after recalibration, and in 6.66% only the pressure of either the low or high-intensity stimulus was increased.

Protocol

During the baseline phase, participants were instructed to categorize the stimuli, (as 'high' or 'low') emphasizing both speed and accuracy (Fig. 1). The allocation of the response buttons to the two categories (i.e., 'high' or 'low') was counterbalanced between participants and the words 'high' and 'low' were shown on the computer screen in the appropriate locations throughout the experiment. In total, 30 S_L and 30 S_H trials were presented across three blocks, with a 3-min break in between blocks. During this break, S_L and S_H intensities were recalibrated if necessary. Inter-trial intervals varied between 7 and 12s. Startle probes were presented 2 seconds before (in 10% of the trials) or 5.5 seconds after stimulus onset (in 30% of the trials). Trials during which a startle probe was presented were excluded from SCR analyses. A pseudorandomized presentation order was adopted with the following restrictions: 1) no more than 1 consecutive trial with a startle probe, and 2) no more than 2 consecutive trials with the same stimulus.

---- Please insert Fig. 1 about here ---

Skin conductance response

Electrodermal activity was recorded with LabLinc V Ag/AgCl electrodes (8 mm diameter, well depth 2 mm) filled with K-Y gel (Johnson & Johnson) and attached to the hypothenar eminence of the palm of the non-dominant hand, which was cleaned with tap water before the start of the procedure. The inter-electrode distance was 2.5 cm. A Coulbourn skin conductance coupler (LabLinc v71-23) provided a constant 0.5 V across electrodes. The signal was digitized at 100 Hz throughout the study.

Data analysis

Peak scoring method

SCRs were calculated by subtracting the minimum skin conductance level (SCL) during the 2s interval preceding balloon inflation from the maximum SCL in the 6 s interval post-stimulus onset. Responses below a value of .05 μS were considered non-responses and reset to 0. Data were log-transformed to reduce the skewness of the distribution of the non-zero responses. Inspection of the SCR distribution revealed a zero-inflated distribution (Fig. 2A). Therefore, we adopted a mixed-effects mixed-distribution model with correlated random effects (Tooze, Grunwald, & Jones, 2002). In essence, the model copes with non-normal zero-inflated data by dividing it into two parts: data with a value equal to zero and those with a value greater than zero. The first logistic component of the model estimates

the conditional probability of occurrence of a nonzero SCR using a logistic model (i.e., occurrence of $SCR > 0$), whereas the second lognormal component estimates the mean of the nonzero values (i.e., magnitude of $SCR \mid SCR > 0$) (see Fig. 2B). To account for repeated measures, random effects for both components of the model were included as well as their potential correlation. These analyses were performed by the freely available SAS macro MIXCORR developed by Tooze et al. (2002), which uses PROC GENMOD and PROC NLMIXED SAS procedures. In the Stimulus model, only Trial Number (to account for SCR habituation) and Physical Intensity (S_L vs S_H) were included as fixed effects, both in the logistic and the lognormal components. The Perception model comprised Trial Number and Perceived Intensity (low vs high). In the Combination model, both Perceived and Physical Intensity (as well as Trial Number) were included. Model comparison was done using Akaike's Information Criterion (AIC), with lower values indicating better fit, for logistic and lognormal components separately. In the case of similar AIC values, the most parsimonious model was preferred. Final parameter estimates of all three models are reported.

Model inversion

Besides using a peak-scoring method, SCRs were also calculated by using a GLM in the PsPM package for Matlab (Bach, Friston, & Dolan, 2013). Because electrodermal activity was not continuously recorded, missing values were entered in the non-recorded time window. PsPM calculates SCRs with a model-based analysis based on the probabilistic inversion of general linear convolution models (Bach et al., 2013). SCR data were normalized and passed through a Butterworth filter (default settings in PsPM). As for the mixed-effects analyses, we ran three GLMs. The "Stimulus GLM" only included Physical Intensity (S_L and S_H), the "Perception GLM" only included Perceived Intensity (i.e. 'high' or 'low') whereas in the "Combination GLM" both Perceived and Physical Intensity were coded (4 markers: S_L – low, S_L – high, S_H – low, S_H – high). Trials without a categorization response were not modeled in any of the GLMs, such that all GLMs were fitted on the same data set. Next, GLMs were compared within individuals using AICs, and the probability of best fit across the entire sample was calculated. Finally, for each of the four different markers of the Combination GLM, related amplitudes were extracted of the reconstructed skin conductance responses [as used by Bach et al. (2013)] and entered in a rmANOVA with Physical Intensity (S_L vs S_H), Perceived Intensity (Low vs High) and their interaction as predictors. Thus, unlike the peak-scoring methods where amplitudes are derived for every trial by subtraction, here one amplitude per condition is derived from the modeled response.

Results

Peak scoring method

As shown in Table 1, for the logistic component the Stimulus model was preferred in terms of goodness-of-fit. In other words, when SCRs were binary coded into either zero or one (indicating a value greater than 0), SCR amplitudes were better predicted by a model that only included Physical Intensity. However, for the lognormal component, both the Combination and Perception model performed better in terms of goodness-of-fit compared to the Stimulus model. The Perception model was preferred compared to the Combination model as it is more parsimonious. Thus, the non-zero SCR amplitudes were better predicted by the model that only included perceived intensities compared to physical intensities.

Effects of Physical Intensity on SCR

In the logistic component of the Stimulus model, we found a significant effect of Trial Number on the probability of a nonzero SCR ($Beta_{logistic} = -.07, SE = .01, p < .001$). That is, zero SCRs were more likely near the end of the experiment. There was also an effect of Physical Intensity ($Beta_{logistic} = .61, SE = .10, p < .001$) with S_H increasing the probability of a nonzero SCR (see Fig. 2C). Furthermore, in the lognormal component of the model that estimates SCR amplitudes for nonzero SCRs, SCR was found to decrease across trials ($Beta_{lognormal} = -.02, SE = .00, p < .001$). Finally, an effect of Physical Intensity ($Beta_{lognormal} = .16, SE = .03, p < .001$) on the SCR amplitude for nonzero SCRs was observed (Table 1) (see Fig. 2D), with higher SCRs for S_H compared to S_L .

Effects of Perceived Intensity on SCR

In the Perception model, we found similar effects of Trial Number ($Beta_{logistic} = -.07, SE = .01, p < .001$; $Beta_{lognormal} = -.02, SE = .00, p < .001$) for both the logistic component and the lognormal component (Table 1). The categorization of the stimulus as high compared to low was associated with an increased probability of a nonzero SCR ($Beta_{logistic} = .75, SE = .10, p < .001$) and a higher SCR amplitude for nonzero SCRs ($Beta_{lognormal} = .21, SE = .03, p < .001$) (see Fig. 2C-D).

Effects of Perceived and Physical Intensity on SCR

In the Combination model, Perceived Intensity was significantly associated with the probability of a nonzero SCR value ($Beta_{logistic} = .60, SE = .12, p < .001$) as well as SCR amplitudes for nonzero SCRs ($Beta_{logistic} = .18, SE = .04, p < .001$): when a stimulus was perceived as high, both the probability of and magnitude of a nonzero SCR value increased (see Fig. 2C-D). Interestingly, the effect of Physical Intensity on SCR amplitudes for nonzero SCRs no longer reached significance ($Beta_{lognormal} = .06, SE = .04, p = .11$) (see Fig. 2C-D). However, it was still significantly associated with the probability of a nonzero SCR value, although less strongly compared to Model 1 ($Beta_{logistic} = .31, SE = .11, p = .007$) (Table 1).

---- Please insert Fig. 2 about here ----

Model inversion

One participant was excluded from these analyses due to problematic model fitting. In 54% of the participants, either the Perception GLM ($N = 22$) or the Combination GLM ($N = 10$) was preferred based on individual AICs, whereas the Stimulus model was preferred in 27 individuals. Next, amplitudes of reconstructed skin conductance responses of the Combination GLM were analyzed with a rmANOVA. Inspection of the SCR distribution, as well as normality tests (Shapiro-Wilk), revealed that the data were normally distributed except for one condition (SL – high), which was due to an outlier. The analyses were run with and without the outlier and showed no difference. Therefore, we report the results of the analyses conducted on the entire sample. We found no main effect of Physical Intensity on the reconstructed amplitude of the skin conductance responses [$F(1,58) = 1.62, p = .21, \eta_p^2 = .027$], while Perceived Intensity significantly influenced SCR amplitudes [$F(1,58) = 14.67, p < .001, \eta_p^2 = .202$]. The interaction between Physical and Perceived Intensity was not significant [$F(1,58) = .005, p = .946, \eta_p^2 = .000$].

Discussion

We investigated the differential contribution of physical and perceived stimulus intensity to the presence and magnitude of the SCR to interoceptive stimuli. To this end, we reanalyzed SCRs of a previous study where two innocuous visceral esophageal balloon distensions with different physical intensities were categorized based on perceived intensity. Our findings suggest that the inclusion of perceived intensity increases model fit of SCR analyses compared to the more typical approach of predicting SCR data solely in relation to physical intensity. However, on an individual level, the inclusion of stimulus perception did not always result in an improved model fit. Future research should further explore these interindividual differences.

In line with previous work, larger SCRs for stimuli of higher physical intensity compared to responses elicited by stimuli of lower physical intensity were observed (Barry & Furedy, 1993; Jackson, 1974; Turpin et al., 1999; Graham Turpin & Siddle, 1979; Vossel & Zimmer, 1992). In addition, we found that the association between physical stimulus intensity and the magnitude of the SCR decreased when categorizations based on the perceived intensity (high or low) were included. We found a strong relationship between the perceived intensity of a stimulus and the strength of the SCR it elicits. For

example, as illustrated in Fig. 2D, SCRs generated by different physical inputs were similar when their perception did not differ.

The pathways by which a physical stimulus triggers psychophysiological responses are complex and subject to different sources of variability which are not always under the control of the researcher. For example, due to changes in both the internal and external environment, the same external stimulus triggers not necessarily the same activity within the sensory system. Although the delivery of stimuli in an experimental context provides the researcher with a high degree of control over the external environment, this is far less the case for the internal environment that comprises changes within the body. Especially, in interoception research, the same physical stimulus can trigger different levels of activity in sensory organs due to variations, for instance, in the compliance of smooth musculature or changes in PH-levels.

Furthermore, identical sensory input can result in different percepts given the inferential process underlying conscious perception. Our findings suggest that in situations where the conscious percept deviates from the physical stimulus, the strength of the elicited skin conductance response is better predicted by the conscious percept compared to the physical stimulus. There is a growing number of studies that record psychophysiological responses to more ambiguous CSs, including interoceptive stimuli or somatosensory sensations, because of their clinical relevance (Ceunen et al., 2015, 2016; Madden et al., 2016; Pappens et al., 2010, 2013; Pappens, Vandenbossche, Van den Bergh, & Van Diest, 2015; Pappens, De Peuter, Vansteenwegen, Van den Bergh, & Van Diest, 2012; Pappens, Smets, Vansteenwegen, Van Den Bergh, & Van Diest, 2012; Schroyen et al., 2015; Zaman et al., 2017; Zaman et al., 2016). Our findings suggest that in situations such as these, where the delivery of physically identical stimuli can be challenging, the inclusion of stimulus perception could help to reduce – otherwise unexplainable – variations in SCR. It would be interesting to further investigate this relationship using various perceptual tasks to assess, for instance, the influence of task characteristics (e.g., perceptual categories vs. ratings) in this context.

In sum, our current findings suggest that inferences based on SCR should be made cautiously as an incongruence between perceived and physical dimensions could influence psychophysiological outcomes. Future research should explore to what extent these findings apply to other customarily adopted psychophysiological measures including startle eyeblink responses, as well as to other stimulus modalities. Furthermore, replication of these findings with an isotonic gel for the measurement of SCR instead of the K-Y gel seems warranted, as the K-Y gel may lead to paradoxical results under unfavorable circumstances (Tronstad, Johnsen, Grimnes, & Martinsen, 2010). We found no differences in SCRs between the gel adopted in the current study and an isotonic variant in a small

control experiment (see supplemental information). However, in anticipation of further research, our findings warrant better control for fluctuations in perceived stimulus features given their association with psychophysiological responses and, hence, their potential to confound results.

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Footnotes

1 Calculated as: $\frac{\sum trials_{ij} with SCR=0}{\sum trials_{ij}}$ with i = index of Physical intensity (S_L vs. S_H) and j = index of Perceived intensity (High vs. Low)

Tables

Table 1. AICs of the mixed-effects mixed-distribution models

Logistic				Lognormal		
Model	Stimulus	Perception	Combination	Stimulus	Perception	Combination
AIC	-8387.7	-7861.3	-7875.7	5425.7	5187.3	5187.1

Table 2. Parameter estimates and standard errors of the mixed-effects mixed-distribution model with correlated random effects

	Logistic			Lognormal		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
FIXED EFFECTS						
Intercept	1.46(.29)***	1.47(.29)***	1.38(.29)***	-2.13(.10)***	-2.13(.10)**	-2.15(.10)***
Physical intensity	.61(.10)***	---	.31(.11)**	.16(.03)***	---	.06(.04)
Trial	-.07(0.01)***	-.07(.01)***	-.07(.01)***	-.02(.00)***	-.02(.00)***	-.02(.00)***
Perceived intensity	---	.75(.10)***	.60(.12)***	---	.21(.03)***	.18(.04)***
Residual	---	---	---	.43(.01)***	.41(.01)	.41(.01)***
RANDOM EFFECTS						
Variance	4.13(.90)***	4.10(.90)***	3.94(.83)***	.51(.11)***	.51(.11)***	.50(.10)***
Covariance	1.10(.27)***	1.07(.26)***	1.03(.25)***			

Physical Intensity was coded as: 0 = S_L, 1 = S_H and Perceived Intensity as: 0 = Low, 1 = High. *** = $p < .001$, ** = $p < .01$

Figure captions

Fig. 1. Overview of trial structure.

Fig. 2. (A) Distribution of SCR data. **(B)** Cross tabs table with physical intensity (S_L vs. S_H) and perceived intensity (High vs. Low) per data set. **(C)** Probability of zero SCR value¹ for perceived intensity (High vs. Low) per physical intensity (S_L vs. S_H). **(D)** Mean SCR for perceived intensity (High vs. Low) per physical intensity (S_L vs. S_H) (red). Only trials with a SCR > 0 are included. S_H = high intensity stimulus, S_L = low intensity

Fig. 3. Mean amplitudes of the reconstructed standardized SCR generated by PSPM (red).

Figures

Fig. 1

Fig. 2

Fig. 3