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A linear model for event-related respiration responses

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HIGHLIGHTS

- We develop a novel method for analysing event-related respiratory responses.
- This method is based on a Psychophysiological Model (PsPM) of interpolated time series.
- We analyse respiration period (RP), amplitude (RA) and flow rate (RFR).
- RA and RFR estimates distinguish different event types, and all three measures distinguish events from non-events.
- The new method could be useful for fMRI experiments using respiration belts.

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ABSTRACT

Background: Cognitive processes influence respiratory physiology. This may allow inferring cognitive states from measured respiration. Here, we take a first step towards this goal and investigate whether event-related respiratory responses can be identified, and whether they are accessible to a model-based approach.

New method: We regard respiratory responses as the output of a linear time invariant system that receives brief inputs after psychological events. We derive average responses to visual targets, aversive stimulation, and viewing of arousing pictures, in interpolated respiration period (RP), respiration amplitude (RA), and respiratory flow rate (RFR). We then base a Psychophysiological Model (PsPM) on these averaged event-related responses. The PsPM is inverted to yield estimates of cognitive input into the respiratory system. This method is validated in an independent data set.

Results: All three measures show event-related responses, which are captured as non-zero response amplitudes in the PsPM. Amplitude estimates for RA and RFR distinguish between picture viewing and the other tasks. This pattern is replicated in the validation experiment.

Comparison with existing methods: Existing respiratory measures are based on relatively short time-intervals after an event while the new method is based on the entire duration of respiratory responses.

Conclusion: Our findings suggest that interpolated respiratory measures show replicable event-related response patterns. PsPM inversion is a suitable approach to analysing these patterns, with a potential to infer cognitive processes from respiration.

1. Introduction

Brain stem centres regulate respiration via autonomic nervous efferents, and these centres are influenced by higher cognitive processes (Lorig, 2007; Ritz et al., 2010; Wientjes and Grossman, 1998). A rich psychobiological literature has addressed how cognitive states impact respiration patterns (Grassmann et al., 2015; Vlemincx et al., 2014; Wuyts et al., 2011), gas exchange parameters (Grassmann et al., 2015), and airway responses (Ritz et al., 2010; Van Diest et al., 2009), and how this may contribute to pathologies such as in asthma (Ritz et al., 2014) or panic disorder (Grassi et al., 2014). In turn, such psychophysiological relationship may allow inferring cognitive states from measured respiration. It is for example known that autonomically controlled skin conductance responses (SCR) (Boucsein, 2012) or heart period responses (HPR) (Bradley et al., 2001) are informative about psychological processes. The analysis of such signals has been formalised in the context of

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Psychophysiological Modelling (PsPM) (Bach and Friston, 2013). A PsPM is usually a combination of a formal (mathematical) model for the neural activity that links psychological processes to the physiological signal under study (neural model), and another model that specifies the relation between neural activity and physiological signal (peripheral model). The combined model is probabilistically inverted to yield the most likely parameters of the neural activity, given physiological data. These parameters characterise the presumed psychological or cognitive input into the system.

Here, we seek to create a PsPM for the relationship between central input and respiratory responses. Crucially, the aim of this PsPM is not to precisely characterise respiratory physiology, but to characterise cognitive states by inversion of the model. This means that even very simple respiratory measures, which may not allow precise quantification of local physiology such as gas exchange or respiration patterns, can be useful as long as they are informative about a psychological process. In cognitive neuroscience research, magnetic resonance imaging (MRI) scanners are standardly endowed with single chest belts for correcting breathing artefacts in MR images (Glover et al., 2000; Hutton et al., 2011). This motivates our present work where we seek to employ this simple measurement system for inferring cognitive states. If successful, this method could thus be harnessed for analysis of a large number of existing datasets, and allow future investigation with existing setups.

In general, there are two methods to develop a PsPM. If the physiological system under study is well-characterised, one may employ such knowledge to create a biophysical model of psychological influences on peripheral physiology, such as the haemodynamic response model in neuroimaging (Friston et al., 2008). More often, however, this is not the case. Alternatively, one may attempt a phenomenological characterisation of the system's input–output relationship. For example, by assuming linearity and time invariance, one can use brief inputs to derive the system's impulse response function. This approach has been fruitful in the context of SCR and HPR (Bach et al., 2009, 2010b; Paulus et al., 2016). Therefore, respiratory responses to brief stimuli would be of primary interest for a respiratory PsPM. As yet, most studies in the field of respiratory psychobiology – including all of the aforementioned work – have addressed respiratory responses to states or stimuli on the timescale of at least 10–20 s up to minutes, or responses to (anticipated) respiratory stimuli (Pappens et al., 2015). However, a few strands of research indicate that an organism's interaction with non-respiratory events on a much shorter time scale also impacts on respiration.

First, the existence of a respiratory orienting response has been proposed by Barry (1977b) who related its magnitude to stimulus novelty (Barry, 1977a). This relationship was confirmed by quantifying respiratory breaks as the duration of the respiration cycle during which a stimulus was presented, measured from start of inspiration (Barry, 1982). This novelty response has later also been termed "surprise" response (Boiten et al., 1994) but has not systematically been investigated after the original proposal. Secondly, intense, unexpected aversive stimulation may elicit "a short-latency [inspiratory] startle response, followed by a delayed phasic increase in depth and rate of breathing" (Boiten et al., 1994). Finally, respiration line length (RLL), quantified as the path length of the respiration trace over a fixed time interval of usually 15 s after an event, has been suggested to differentiate between crime-relevant and crime-irrelevant items in the concealed information test, one of the few validated tests for detection of deception in the polygraph field (Matsuda and Ogawa, 2011).

Taken together, this suggests that respiratory breaks, and phasic changes in respiratory period and amplitude, might be informative about cognitive processes. The single-belt system employed here allows assessing respiration timing, while for precise quantification of respiratory amplitude, a double-belt system would be required to measure both thoracic and abdominal compartments (Binks et al., 2007). However, if the ratio between thoracic and abdominal contribution is relatively constant within any individual, it may still be possible to approximate respiratory amplitude up to a linear constant from the single-belt system. This is why we ask empirically whether measures of respiration amplitude allow a meaningful inference on psychological state.

We propose a PsPM approach based on continuous data and linear time-invariant systems, as in previous work on skin conductance (Bach et al., 2009; Bach et al., 2010b; Bach and Friston, 2013; Bach et al., 2010c) and heart period responses (Castegnetti et al., 2016; Paulus et al., 2016). We are interested in evoked responses to events in the outside world that are non-synchronised to respiration. This means that time after stimulus onset does not correspond to particular fixed time points in the respiration cycle. To solve the problem of assigning respiratory-cycle based measures to real time, we follow a strategy commonly employed in analysis of heart period responses, namely, linear interpolation (Berntson et al., 2007). We capitalise on an established modelling framework (Bach and Friston, 2013), to build a phenomenological forward model of how cognitive input impacts respiration period. This forward model is combined with a model inversion method. This provides for inference on the amplitude of central input from measured data, and is embodied in a general linear convolution model (GLM). All algorithms are publicly available as part of a Matlab toolbox for Psychophysiological Modelling, PsPM (previously termed SCRalyze, http://pspm.sourceforge.net).

2. Method

2.1. Participants

We recruited from the adult student population via advertisements 30 participants for experiments 1–2 (23 female, mean age ± standard deviation: 23.4 ± 3.6 years). From this sample, 5 persons did not participate in the electric stimulation task 2, and 4 datasets from task 1 were discarded due to marker malfunction, such that we report 26 datasets for experiment 1 and 25 datasets for experiment 2. Twenty participants took part in experiment 3 (12 female, 22.2 ± 3.6 years), and an independent sample of 20 participants in validation experiment 4 (9 female, 25.3 ± 5.1 years). In experiment 3 we also recorded heart period which was included in a previous methodological investigation (Paulus et al., 2016). All experiments and the form of taking written informed consent were approved by the competent research ethics committee (Kantonale Ethikkommission Zürich, KEK-ZH Nr. 2013-0118 and 2013-0258).

2.2. Procedure

2.2.1. General considerations

We were interested in characterising phasic respiratory changes that differentiate different experimental events, which we selected with an eye on previous findings. One dimension supposedly eliciting phasic respiratory changes is stimulus *novelty*, operationalised previously by repeating simple auditory or visual stimuli in a detection task (Barry, 1977a, 1982). Experiment 1 therefore realised a visual detection task with 10 target repetitions. Another relevant class are *intense, aversive* stimuli (Boiten et al., 1994). This was realised in experiment 2 using unpredictable and discomforting electric stimulation. Finally, *crime-relevance* is a dimension known from applied psychology to elicit phasic respiratory responses (Matsuda and Ogawa, 2011), and is possibly related to emotional arousal. As we were not interested in crime-relevance as such, we investigated emotional arousal by showing pictures with high