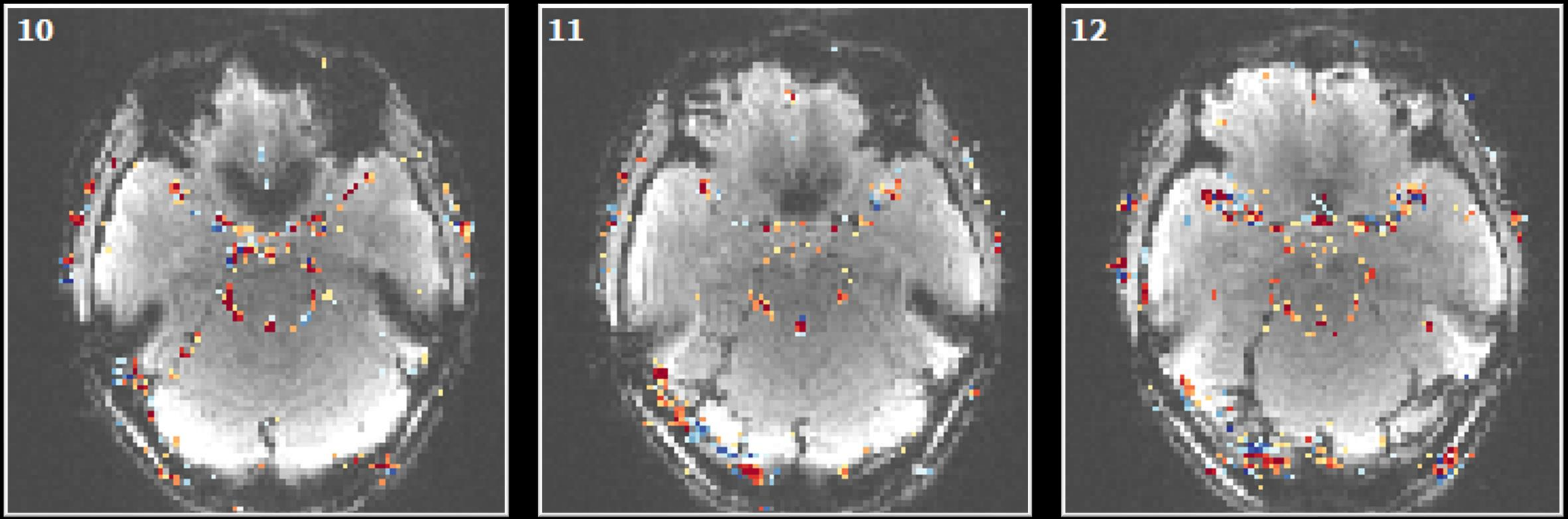


Physiological Noise Correction Using External Recordings

10-12-2021

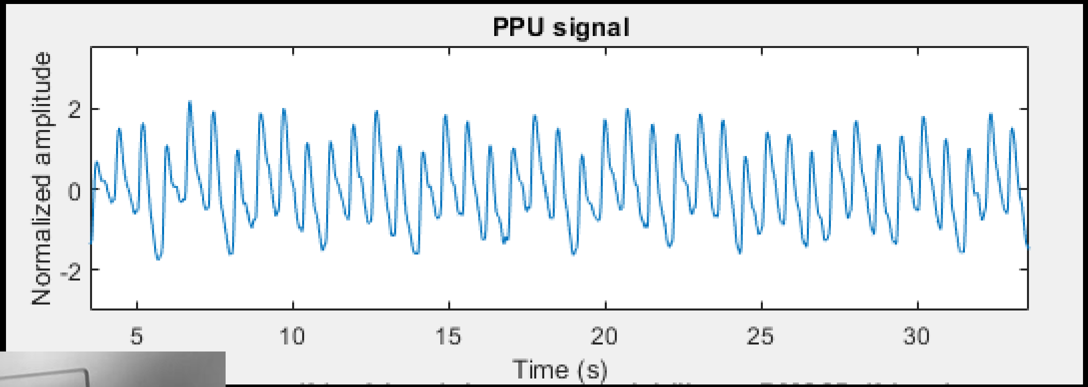
Background:
Why is Physiological Noise Problematic

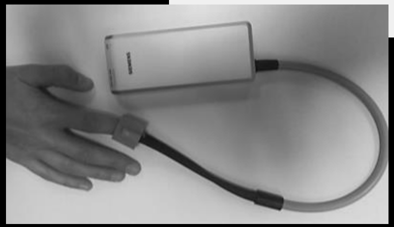
- fMRI signal consists of neuronal-related signal changes of interest and of non-neuronal signal contributions that are considered noise, with the former one being relatively small as compared to the noise
- Disentangling the neuronal component of the BOLD signal from physiological and measurement confounds is challenging
- Increasing spatial and temporal resolution requires higher field strengths, but with higher field strengths sensitivity to non-neuronal noise also increases
- In turn the increased signal variance due to physiological noise effectively decreases signal detection power
- Because of the structured nature of the physiological signal component, the assumption of independent and identically distributed residuals in many fMRI analyses is compromised
- Physiological noise is specifically problematic in connectivity analyses as physiological-related fluctuations tend to introduce common variance in the signal of independent brain regions resulting in inflated correlations between brain regions affected by physiological noise
- In task-based fMRI cardio-respiratory processes can vary with task demands introducing correlations with the task design, resulting in a possible interpretation bias of task related BOLD signal changes, examples are motor tasks, experimental pain studies and neurofeedback designs (Weiss et al., 2020)
- Significant group differences in relevant fMRI outcome measures between clinical populations might be biased by differences in physiological responses between these groups (e.g. Li et al., 2021)

Background:
Monitoring Cardiac and Respiratory Physiology in the Periphery

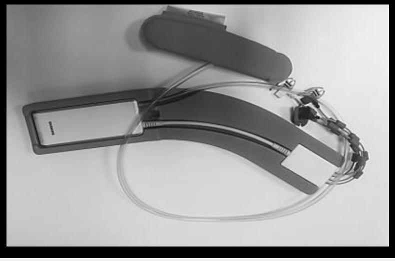
(Bulte & Wartolowska, 2017)

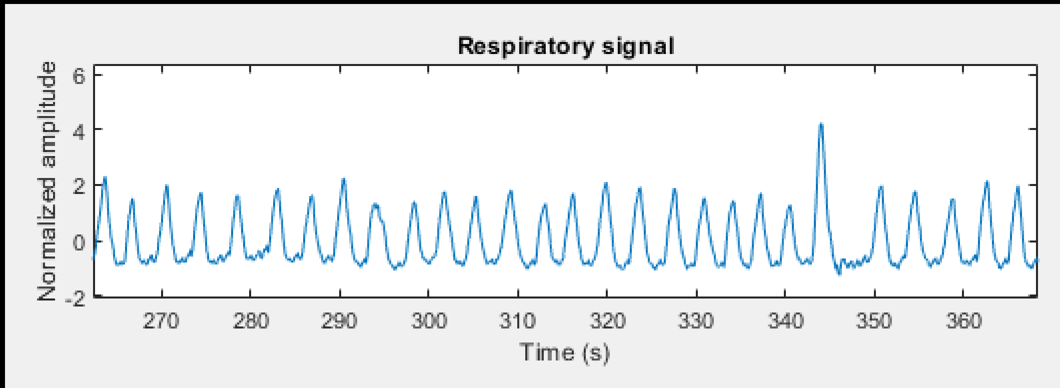
- Cardiac data:
  - Usually collected via an infrared pulse oximeter in the form of a finger clip
  - used to measure the pulsatile component of the cardiac cycle (heart rate)
  - changes in blood volume caused by the pressure pulse detected via changes in light absorption
  - Subjects should not wear nail polish
  - cable should be aligned with the B0 magnetic field to avoid induced signal errors by scanner gradients
  - Sensitive to finger movement





- Respiratory data:
  - Often recorded by a mechanic pneumatic belt wrapped around the abdomen/chest
  - measuring the tension on the belt
  - The breathing motion is tracked to indicate end-inspiration and end-expiration
  - belt should hold the cushion tight, but loose enough that the cushion expands and contracts with each breath
  - Sensitive to respiratory, but also non-respiratory motion if it involves abdomen

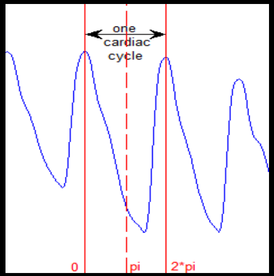


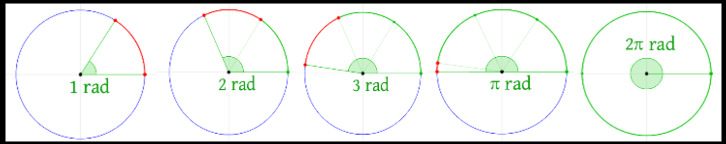


Background:
Cardiac and Respiratory Cycle

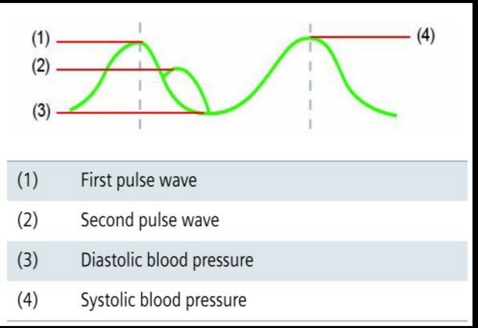
Cardiac cycle

- One cardiac cycle takes about 0.8 to 1 seconds, ~ 1.2 Hz, and ranges from 0 to 2 pi radians (2pi = 360 degrees)





source: Wikipedia

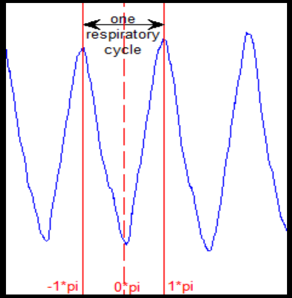


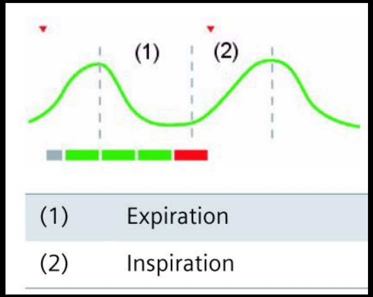
source: Prisma guide

- it can be described by the heart rate (HR) which is expressed in beats per minutes (bpm)
- HR changes with the need of increased oxygen, i.e., exercise, sleep, anxiety, stress, illness, drugs, etc.
- HR at rest varies between 60 and 100 bpm

Respiratory cycle

- One respiratory cycle takes about 3-5 seconds, ~0.3 Hz, and ranges from –pi to pi





source: Prisma guide

- it can be described by the breathing or respiratory rate (BR) which is expressed in respiratory (breaths) per minutes (rpm)
- Breathing patterns vary among individuals, and are influenced by pain, emotion, body temperature, sleep, body position, activity level, and disease
- BR at rest varies between 12 and 20 rpm

Background: Categorization of Physiological Noise (Kassinopoulos et al., 2021, Neuroimage)

Systemic Low Frequency oscillations (SLFOs) ~ 0.1 Hz in fMRI -

- purely blood-borne signals
- signals driven by changes in the levels of deoxy-Hb in the sample being imaged
- influenced by several physiological factors, like:
    - Variations in heart rate (Shmueli et al., 2007)
    - Levels of carbon dioxide (Wise et al., 2004)
    - Breathing patterns (Birn et al., 2006)
    - Arterial blood pressure (Whittaker et al., 2019)

Acquisition Artifacts

- Caused by motion
- have a direct impact on the acquisition process:
    - Bulk head motion
    - Breathing-related chest expansion -> changes in static magnetic field -> image shift in phase-encoding direction -> fMRI volume distortions
    - Cardiac pulsatility leads to vessel pulsation in the brain vasculature and associated tissue movement (cerebrospinal fluid movement)-> local artifacts near ventricles, sulci, and large vessels as well as tissue deformation

Background:
Localizing High and Low-Frequency Cardiac and Respiratory Effects

High-frequency cardiac noise ~1 Hz (Cordes et al., 2014; Birn et al., 2006):

- effects of pulsatility of blood flow = rather local effects
- Cardiac pulsations present in regions of high blood volume or CSF, so near major blood vessels (e.g. Circle of Willis or sagittal sinus) and ventricles or and near spinal cord regions (strong vibration associated with heartbeat)

High-frequency respiratory noise ~0.3 Hz (Cordes et al., 2014):

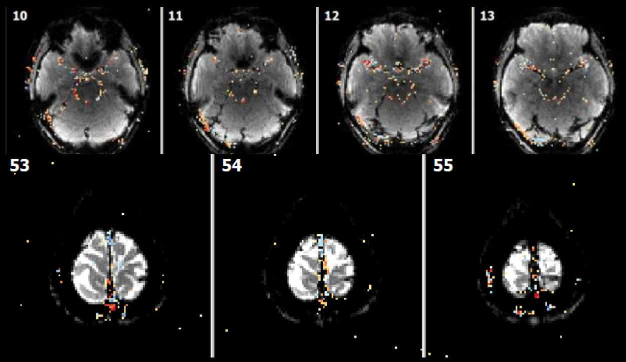
- respiration-induced magnetic field changes and breathing motions = rather global effects
- Respiration-induced motion artifacts near the edges of the brain (primarily in the phase encoding direction - consistent with a magnetic field shift in synchrony with the chest movement)

Low-frequency cardiac noise (< 0.1Hz) :

- Due to variations in heart rate (~0.04 Hz) (Shmueli et al., 2007)
- Particularly in grey matter, less so in white matter (since GM is more highly vascularized than WM)
- occipital and posterior cingulate areas significantly correlated with both cardiac rate and respiratory volume

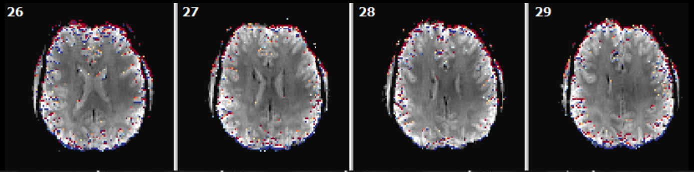
Low-frequency respiratory noise (< 0.1 Hz) (Birn et al., 2006):

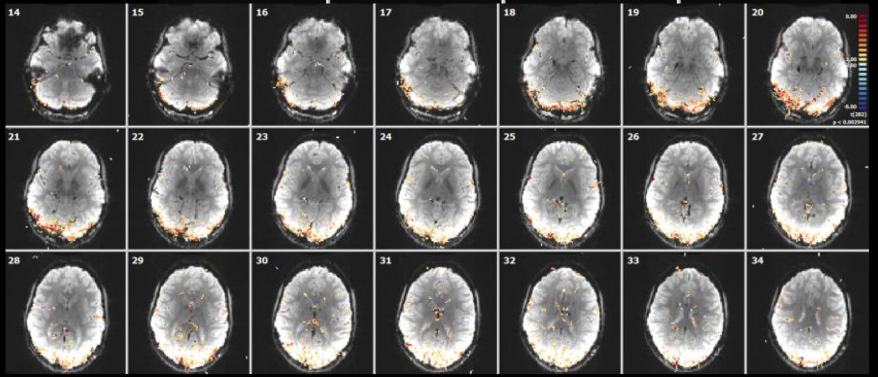
- Changes in breathing rate and/or depth result in changes of respiratory volume and in fluctuations of arterial CO_2
- Hypercapnia (from breath-holding) increases BOLD signal, hypocapnia (from hyperventilation) reduces BOLD signal
- Already small fluctuations of arterial CO_2 are correlated with the BOLD signal in the cerebellum, insula, frontal and sensory cortex and in the occipital, temporal and posterior parietal cortex (Wise et al., 2004)



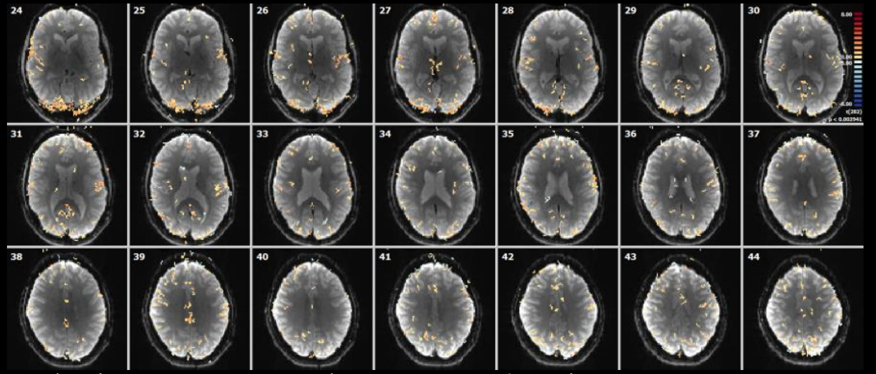
RETROICOR cardiac, order= 3
3T, TR: 2, MB2, 2x2x2 mm, Data: 3DMC

RETROICOR respiratory, order= 4
7T, TR: 1, MB3, 2x2x2 mm, Data: 3DMC





HR*CRF (heartrate* cardiac response function),
3T, TR: 2, MB2, 2x2x2 mm, Data: 3DMC, undistorted, RETROICOR, SSTC



RVT*RRF (respiration-volume-per time * respiratory response function),
3T, TR: 2, MB2, 2x2x2 mm, Data: 3DMC, undistorted, RETROICOR, SSTC

Background:
Modelling the high-frequency component of physiological noise using external recordings, RETROICOR (Glover et al., 2000)

- Retrospective Image Correction (RETROICOR) was developed for whole-brain fMRI
- physiological noise (respiration motion & cardiac pulsatility) is removed by:
  1. Assigning a cardiac and respiratory phase to each data point based on its acquisition time relative to the physiological cycles
     - Phase of the cardiac cycle: time to the nearest preceding heart beat / the time between the heart beats
     - Phase of the respiratory cycle: depth of the breath at the time of the image acquisition relative to a histogram (scaled from 1 to 100) of the respiration depth across the entire imaging run
  2. Then modelling their likely effect on imaging data using a basis set including 4-6 Fourier terms

- Modified version which is implemented via the GLM :
  - Fourier analysis can be used to model noise in the data
    - 4 – 6 terms for cardiac (sine/cosine)
    - 4 – 6 terms for respiratory (sine/cosine)
    - Interaction terms
  - These low-order Fourier-series are fitted to the imaging data to account for signal variations due to PHASE only

- Changes in respiratory rate or heart rate are NOT accounted for by RETROICOR
- Hence task-dependent changes in respiration rate or depth CANNOT be corrected for with RETROICOR

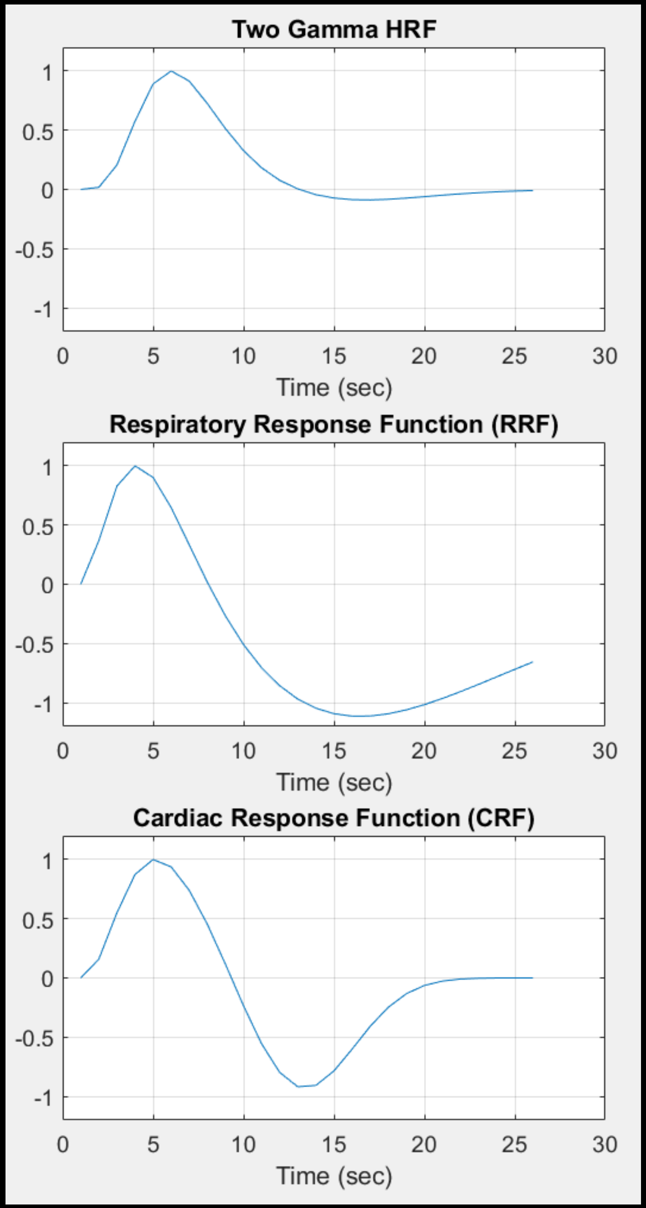
Background:
Modelling the low-frequency component of physiological noise using external recordings

Respiration

- Changes in breathing rate and depth, result in changes of
  - ↓Exhaled CO2 -> ↑arterial pCO2 concentration -> ↑cerebral blood flow -> BOLD signal changes
- One way to correct for these changes is the use of a respiration measure in a nuisance regression
- The following measures have been proposed (among others):
  - ENV – windowed envelope of the respiration waveform
  - RVT – Respiration Volume per Time
  - RV – Respiratory Variation – windowed variation of the respiration waveform
- Time-shifted versions of these predictors can be used to account for the variable delay between the respiration changes and the fMRI signal change
- But the explanatory power of these measures is best, when convolved with a respiratory response function (RRF, e.g. Birn et al., 2008) that takes into account the different timing of fMRI signal changes in response to changes in breathing
  - Which appear to be different than neuronally induced BOLD signal changes and are therefore not modeled accurately using the typical HRF
- Different response functions have been derived from widely spaced instructed deep breaths, cued depth and rate changes or isolated spontaneous deep breaths in subjects at rest, with these functions being quite similar

Cardiac

- Fluctuations in Cardiac Rate (Shmueli et al., 2007, Biancardi et al., 2009)
- Time-shifted versions of the cardiac rate predictor to account for variable delays
- Alternatively, cardiac rate convolved with a physiological response function – the cardiac response function (CRF, Chang et al., 2009) to characterize the mapping between heart rate and BOLD signal



Background:
Different Effects of Physiological Noise Depending on Field Strength, Sequence, Task Design and Subject

Field Strength

- Hutton et al., 2011: improvement of tSNR in 7T , with strongest improvements for lower resolution

Sequence and Acquisition Parameters, Analysis

- Cordes et al., 2014: Data correction better for smoothed data as larger effect of the low-frequency physiological response functions on the data correction
- Chen et al., 2019: Considerations for fast TRs: Weighing the advantage of pure temporal filtering versus additional model-based correction for short TRs
- Kassinopoulos et al., 2021: Possible dependence on phase encoding direction observed
- Tijssen et al., 2014: Optimal correction model, in terms of the included physiological noise predictors (phase and/or rate predictors), varies between different 3D acquisitions

Task

- Munck et al., 2008: heart rate variations contain important physiological information about subject's resting state
- Birn et al., 2009: Task-correlated breathing
- Iacovella & Hasson, 2011: Noise or Signal – when analysing autonomic nervous system (ANS) functions
- Khalili-Mahani et al., 2013: Physiological Noise Correction in pharmacological resting state

Subjects

- Chang et al., 2009: relative contribution of heart rate and respiratory volume to BOLD fluctuations was not uniform across subjects
- Cordes et al., 2014: amount of affected voxels by physiological noise varied significantly across subjects

Background:
Order of preprocessing steps for physiological noise correction

RETROICOR

- As early as possible in the preprocessing chain, as RETROICOR is sensitive to signal interpolation:
- One possibility: motion correction, EPI distortion correction, RETROICOR, Slice-Scan-Time Correction
- Studies using HCP data most often used the minimally processed data (gradient-nonlinearity induced distortion correction, MoCo, EPI distortion correction, registration to MNI, high-pass filtering (2000 s) – all applied in one step) and then used nuisance regression on these datasets

Jones et al., 2008: Optimal Order for RETROICOR at 7T:

- R – realignment
- C – correction (RETROICOR)
- T- timing (slice time correction)

Slow respiratory and cardiac changes

- Can be included as confounds in the design or can be used in a nuisance regression saving the cleaned data
- some of the studies employing the HCP data used slightly smoothed data for nuisance regression
- Be aware! when changes in these physiological measures are correlated with the task, regressing out these effects, might become problematic since the BOLD response to the task itself may be removed

Hallquist et al., 2013: Bandpass filtering and nuisance regression in resting state fMRI:

- Simultaneous filtering of data and regressors to avoid reintroducing noise in the data
- Do not perform filtering before nuisance regression

CreatePhysioPredictors_BIDS.m

Matlab script for generating a set of respiratory and cardiac noise regressors

Required Toolboxes and Input Files

- Neuroelf: https://neuroelf.net
- Scanning Parameters extracted from BrainVoyager's FMR file (generated with BV 21.4 or newer)
- Physiological Data in accordance with the BIDS standard:
  - * _Physio.json and
  - *_Physio.tsv.gz
- Optional: Task Design Matrix via BrainVoyager's SDM file (to correlate physiological measures with task predictors)

sub-01_ses-04_task-blocked_run-1_bold_Physio.json - Notepad

File Edit Format View Help


```
{
"SamplingFrequency": 400.00,
"StartTime": -25.567,
"Columns": ["cardiac", "respiratory", "trigger"]
}
```


sub-01_ses-04_task-blocked_run-1_bold_Physio.tsv - Notepad

File Edit Format View Help

```
1579.000000     1061.000000     0.000000
1579.000000     1061.000000     0.000000
1573.000000     1061.000000     0.000000
1573.000000     1061.000000     0.000000
1568.000000     1061.000000     0.000000
1568.000000     1061.000000     0.000000
1563.000000     1061.000000     0.000000
1563.000000     1061.000000     0.000000
```

sub-01_ses-04_task-blocked_run-1_bold_TASK.sdm - Notepad

File Edit Format View Help

```
FileVersion:            1

NrOfPredictors:         7
NrOfDataPoints:         291
IncludesConstant:       1
FirstConfoundPredictor: 7

200 43 43   200 200 43   43 200 43   43 200 200   43 43 200   200 43 200   255 255 255
"Faces_LVF" "Houses_RVF" "Faces_CVF" "Houses_LVF" "Faces_RVF" "Houses_CVF" "Constant"
  0.000000   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.000000   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.000000   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.000000   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.086566   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.461454   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  0.846378   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
  1.062495   0.000000   0.000000   0.000000   0.000000   0.000000   1.000000
```

Output Files

- Naming scheme:
  - all newly created files are saved in a subfolder of the FMR, called “PhysioOut” and start with the name of the FMR

1. *_cardiacrespiratory.mat (file name includes the physio.colheader without the trigger columns
2. *_cardiac.png & *_cardiac.fig
3. * _cardiac_BP0.5-8Hz_z.sdm
4. * _cardiac_RETROICOR.sdm
5. *_HR.sdm
6. *_HRCRF.sdm
7. *_resp.png & *_resp.fig
8. *_resp_filtz.sdm
9. *_resp_RETROICOR.sdm
10. * _cardiacresp_RETROICOR.sdm
11. *_BR.sdm
12. *_RF.sdm
13. *_ENV.sdm
14. *_RVT.sdm
15. *_RVTRRF.sdm
16. *_TaskNoiseCorr.png & *_TaskNoiseCorr.fig

physio

1x1 struct with 27 fields

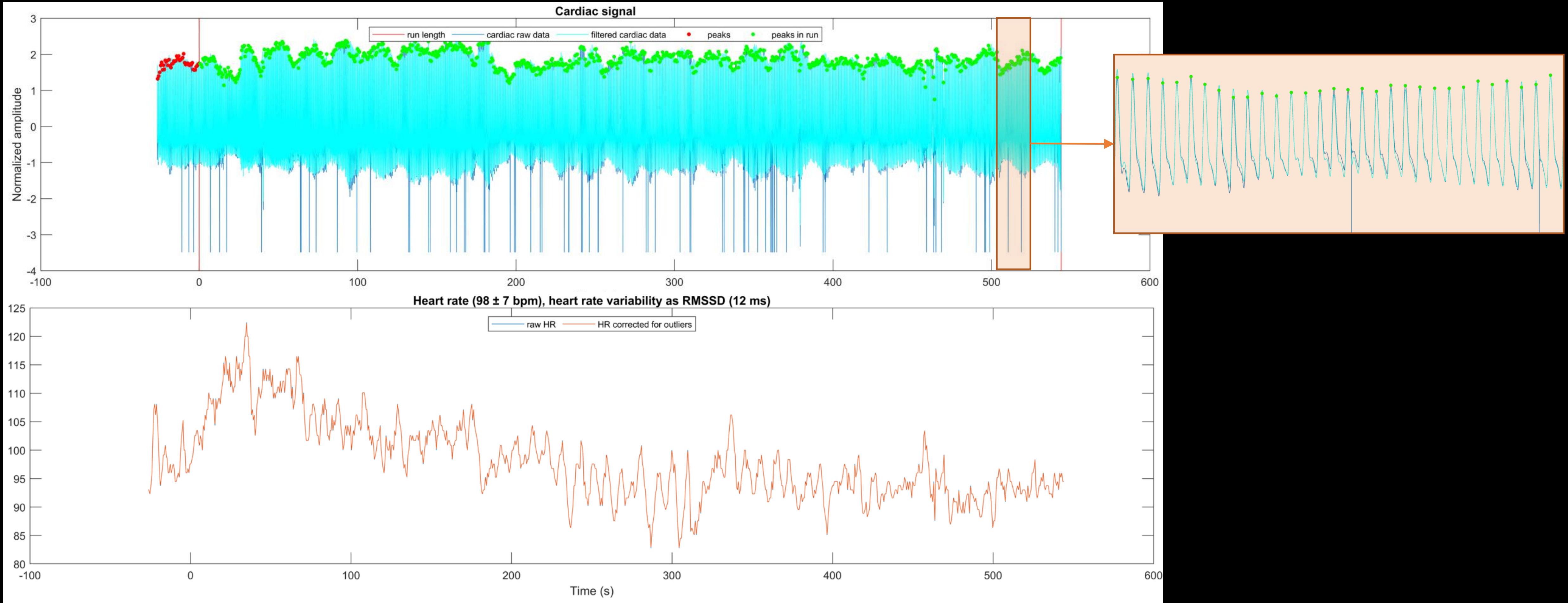
Field	Value
scriptname	'CreatePhysioPredictors_BIDS.m'
scriptversiondate	'09-Nov-2021 14:11:17'
currentdate	1x1 datetime
Hz	400
startsec	-26.4000
colheader	1x3 cell
data	1x1 cell
NoOfTriggerIntervals	8704
TR	2000
NoVols	272
NoSlices	64
SliceTimingTableSize	64
SliceTable	64x1 double
SliceTimes	32x1 double
time	1x1 cell
PPGpeaks_ind	1x933 double
PPGpeaks_loc	1x933 double
hbi_rmssd	12.2825
HRmean	98.1261
HRstd	6.8154
Regressors	1x1 struct
RESPpeaks_ind	1x171 double
RESPpeaks_loc	1x171 double
BRmean	18.4740
BRstd	3.4961
Task	1x1 struct
TaskNoiseCorr	1x1 struct

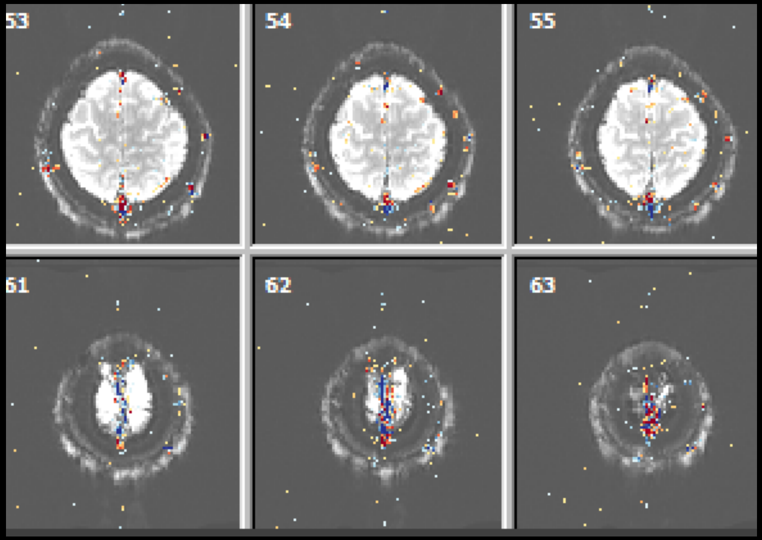
Output Files (1)

1. *_cardiacrespiratory.mat
   - Contains structure called physio with different parameters extracted from the *_Physio.json and the *_Physio.tsv.gz as well as the FMR:
     1. scriptname: script that was used to create this mat file
     2. scriptversiondate: date and time the script was edited last
     3. currentdate: date the script was ran with the current data set
     4. Hz: sampling frequency of physiological signal
     5. startsec: delay with respect to fMRI sequence start, defined in seconds
     6. colheader: data traces available in *_Physio.tsv.gz (e.g. cardiac, respiratory, trigger)
     7. data: data traces from *_Physio.tsv.gz
     8. NoOfTriggerIntervals: number of volume triggers or number of volume * slice triggers
     9. TR: repetition time of functional scan
     10. NoVols: Number of Volumes in FMR (without skipped volumes)
     11. NoSlices: No of Slices in FMR document
     12. SliceTimingTableSize: Number of Slices for which slice acquisition time stamps exists in volume
     13. SliceTable: Slice Acquisition Time Stamps
     14. SliceTimes: Unique Slice Acquisition Times (important for Multiband sequences)
     15. time: time stamps of data points in seconds with respect to onset of fMRI run
     16. PPGpeaks_ind: Indices of identified pulse peaks in data trace
     17. PPGpeaks_loc: time stamps in seconds of identified pulse peaks
     18. Hbi_rmssd: root mean square of successive differences between normal heartbeats, quantifies the amount of heart rate variability in measurement period
     19. HRmean: mean heart rate in data trace, calculated based on the identified pulse peaks
     20. HRstd: standard deviation of heart rate in data trace, calculated based on the identified pulse peaks
     21. Regressors: structure of all physiological noise regressors and the corresponding names
     22. RESPpeaks_ind: Indices of identified respiratory peaks in data trace
     23. RESPpeaks_loc: time stamps in seconds of identified respiratory peaks
     24. BRmean: mean breathing rate in the data trace, calculated based on the identified respiratory peaks
     25. BRstd: standard deviation of breathing rate in data trace, calculated based on the identified pulse peaks
     26. Task: structure of all task predictors and the corresponding names (if a task design matrix was defined by the user)
     27. TaskNoiseCorr: Structure with pearson correlation values and the respective significance values for all noise-task regressor pairs

Output Files (2)

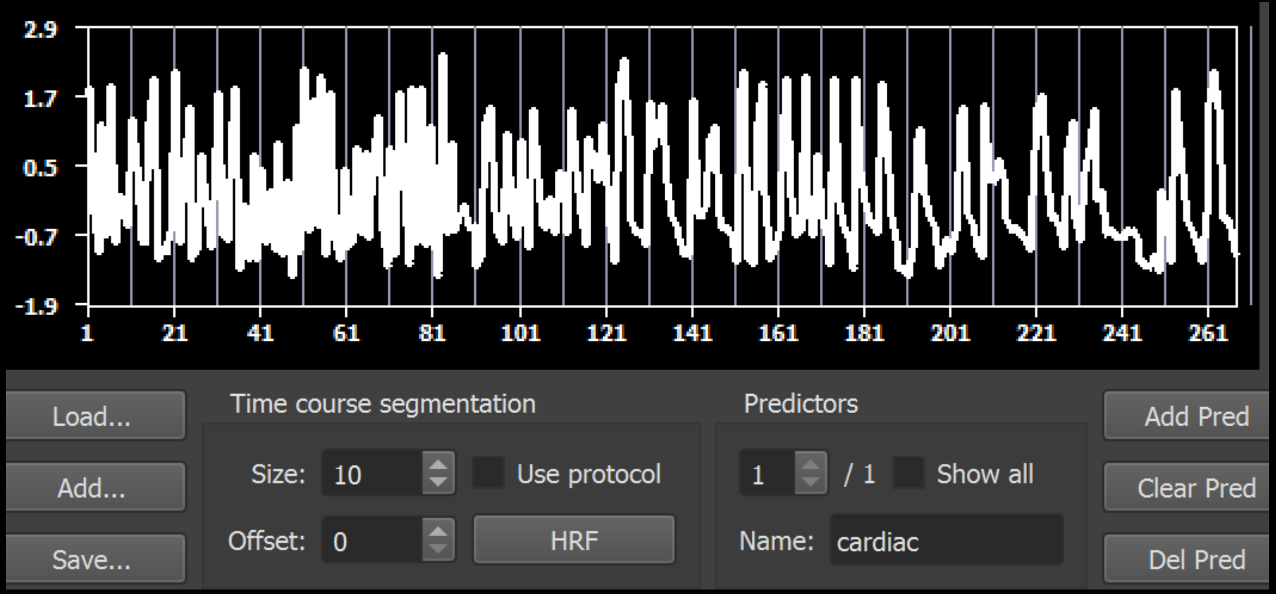
2. *_cardiac.png & *_cardiac.fig
   - Figure showing the unfiltered and filtered raw data, together with the identified peak locations of the signal within the run, as well as the start and end of the run
   - The second sub-plot shows the heart-rate of the participant and the same signal corrected for outliers (sudden changes)

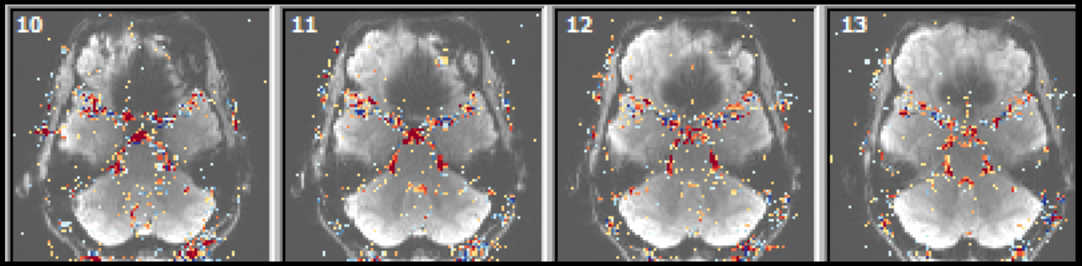


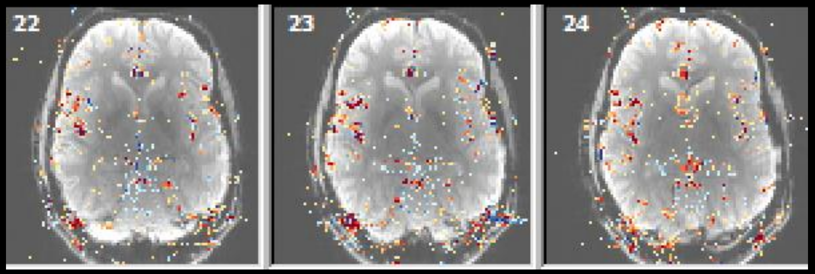


Output Files (3)

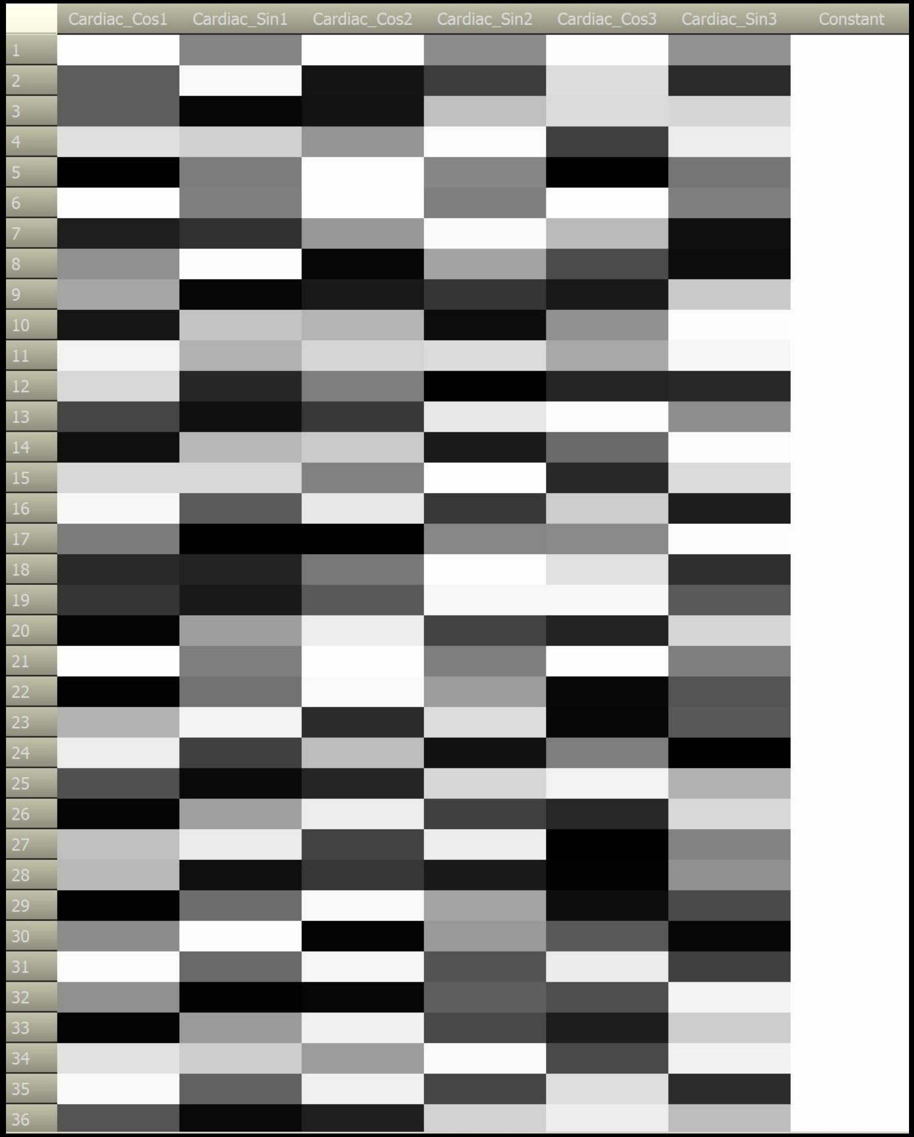
3. * _cardiac_BP0.5-8Hz_z.sdm
   - Data trace filtered with a zero-phase digital bandpass filter between 0.5 and 8 Hz to eliminate slow drifts and spikes
   - z-transformed



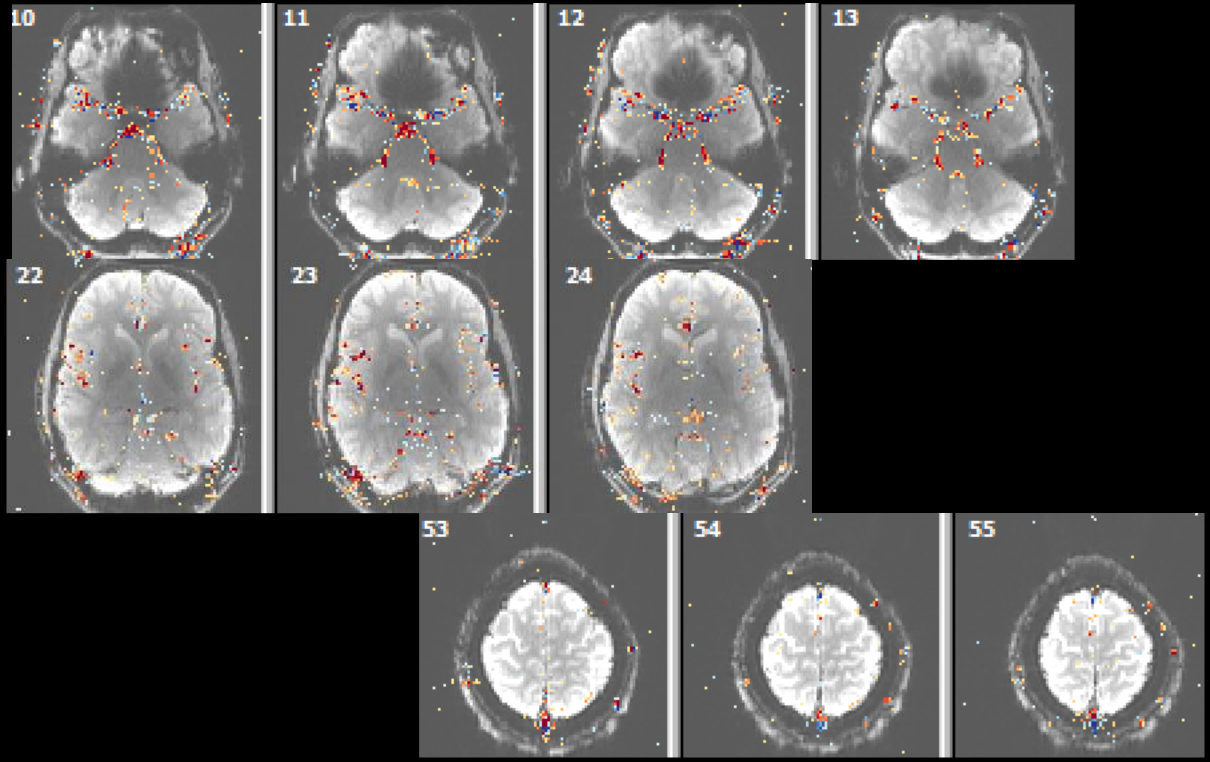




Output Files (4)

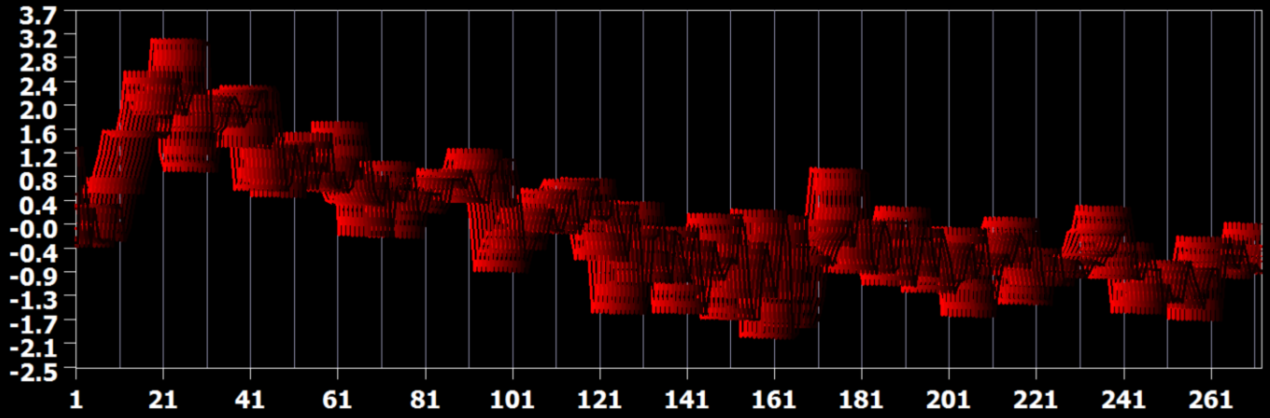


4. * _cardiac_RETROICOR.sdm
    - Cardiac RETROICOR predictors
    - Default number of cardiac harmonics (N3) based on Harvey et al., 2008 (Brainstem imaging)

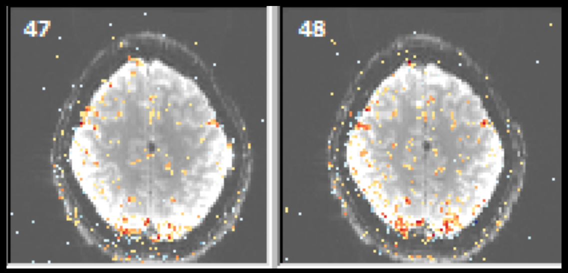


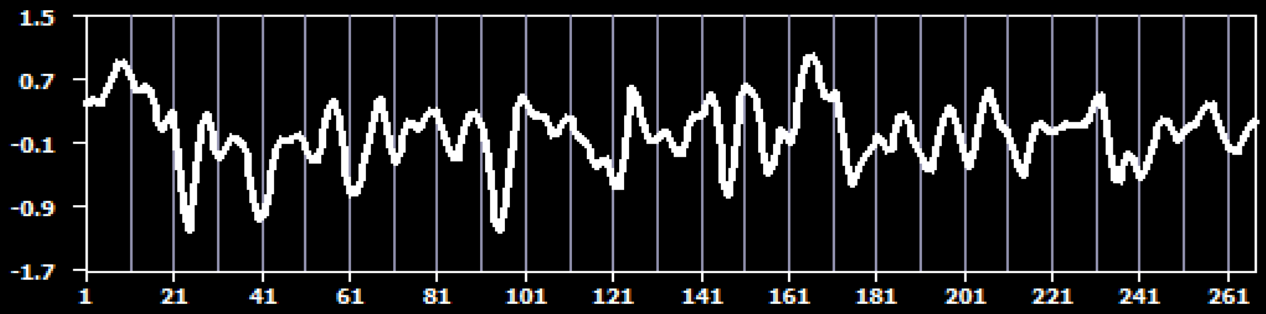
Output Files (5 & 6)

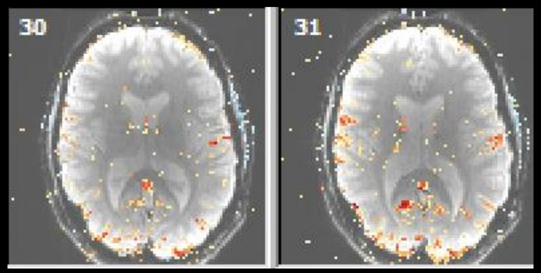
5. *_HR.sdm
   - N shifted heart rate regressors
   - Number of regressors and time difference between consecutive shifts can be specified by user
   - Default: HR_shift0:2:HR_shift24 seconds (based on Shmueli et al. . 2007)



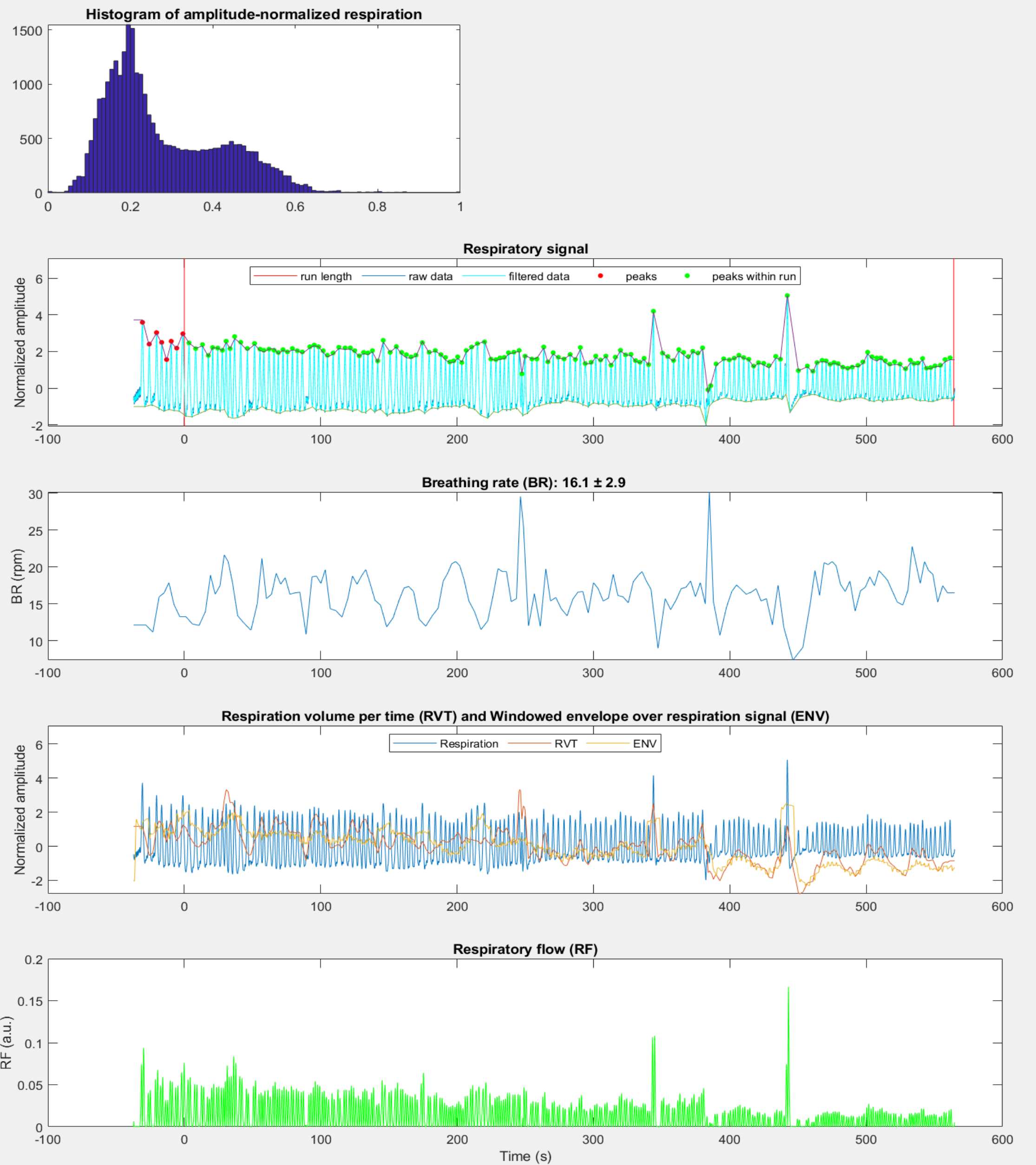
6. *_HRCRF.sdm
   - heart rate regressor convolved with the cardiac response function (CRF) by Chang et al., 2009







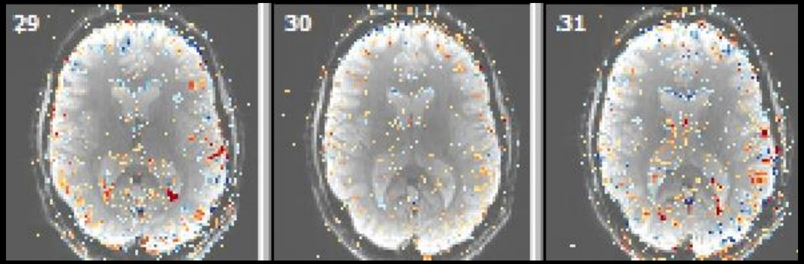
Output Files (7)



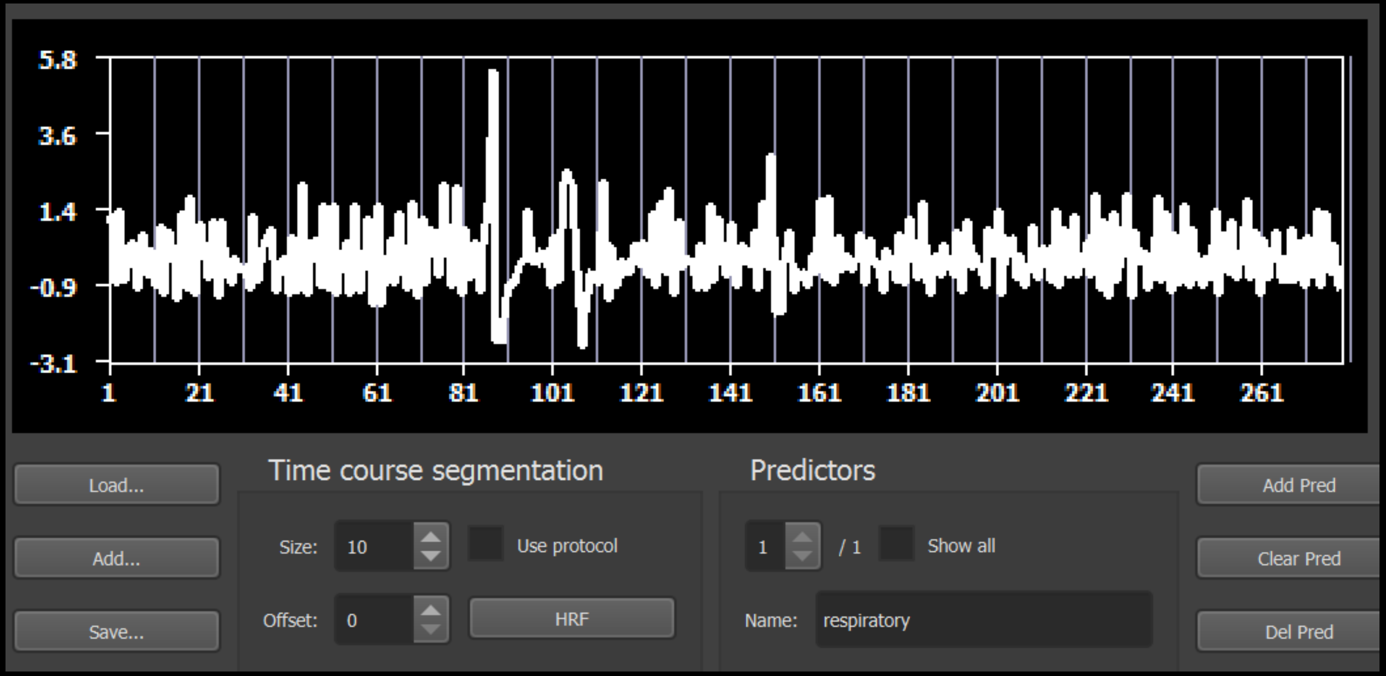
*_resp.png & *_resp.fig

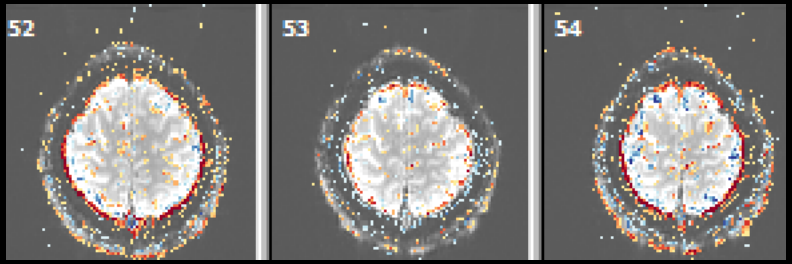
- Subplot 1: histogram to judge breathing amplitudes
- Subplot 2: showing the unfiltered and filtered raw data, together with the identified peak locations of the signal within the run, as well as the start and end of the run
- Subplot 3: breathing rate within the run (respirations (breaths) per minute – rpm)
- Subplot 4: filtered and z-transformed respiratory signal in relation to the respiratory volume per time and the envelope of the signal
- Subplot 5: respiratory flow (RF) = absolute flow of inhalation and exhalation at each time point (in arbitrary units)

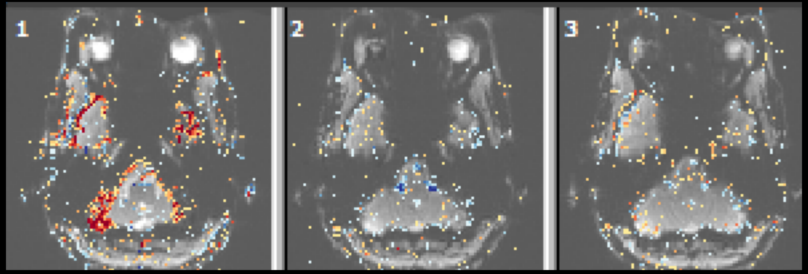
Output Files (8)



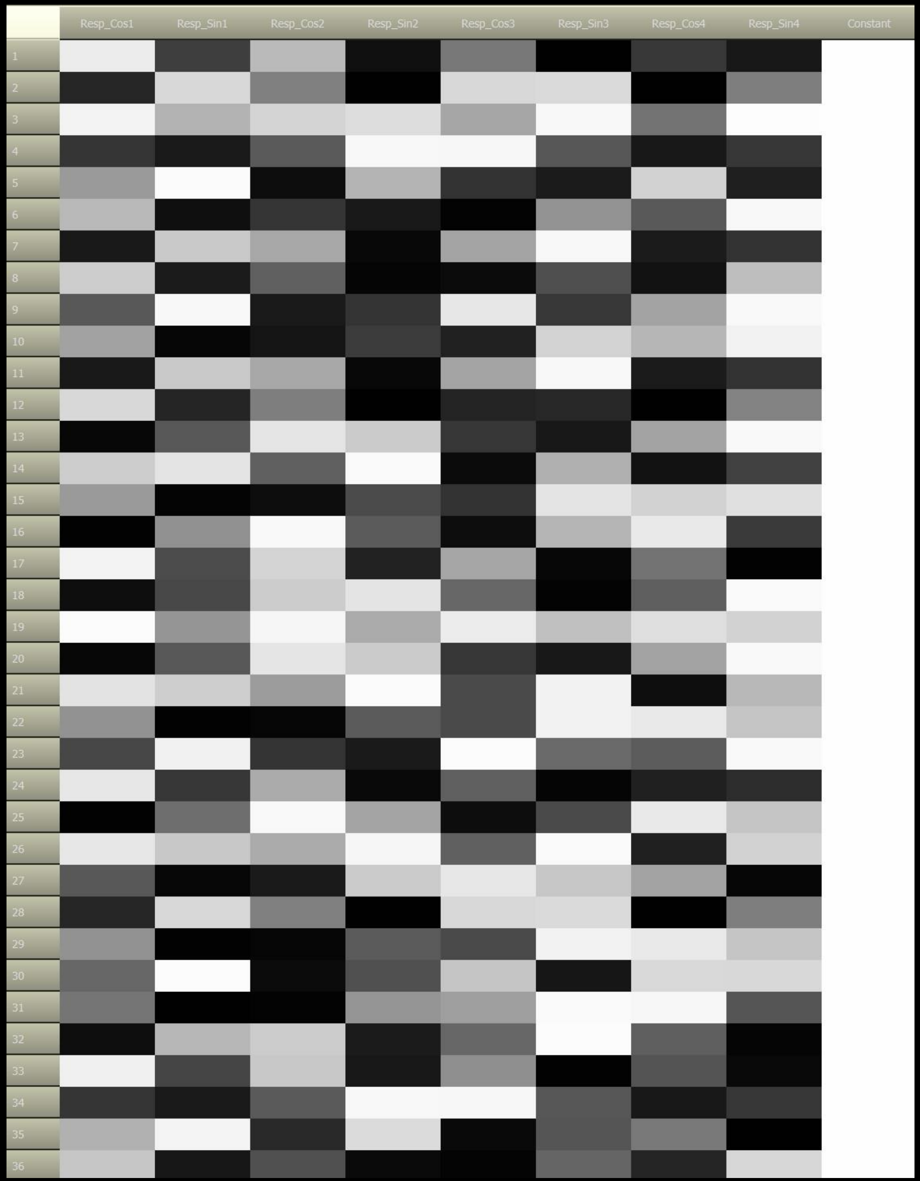
8. *_resp_filtz.sdm
   - Filtered (detrended, outliers removed, smoothed) and z-scored respiratory signal
   - sampled at t = 0 of each TR



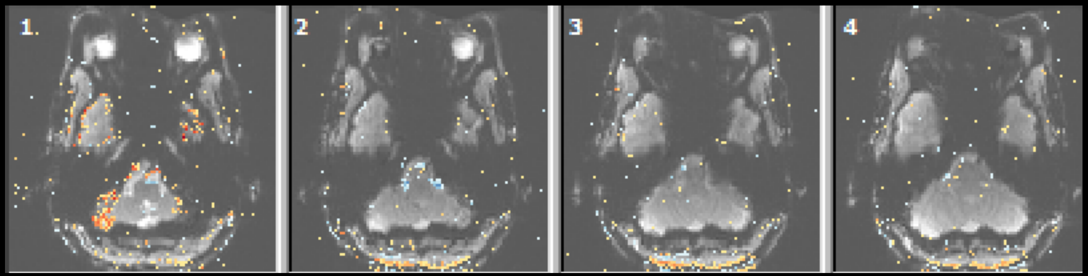




Output Files (9)

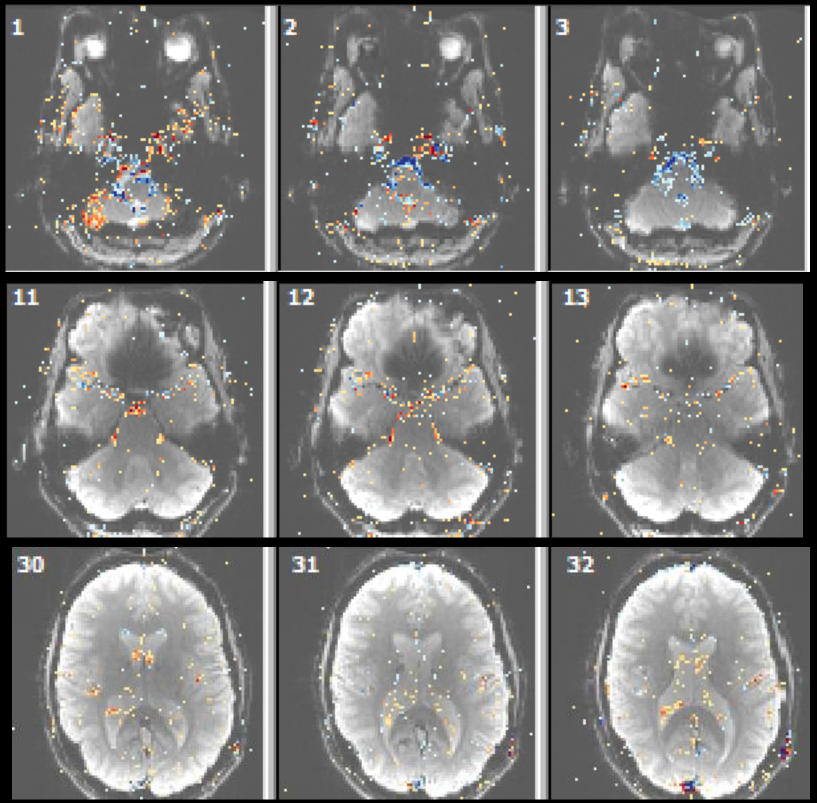


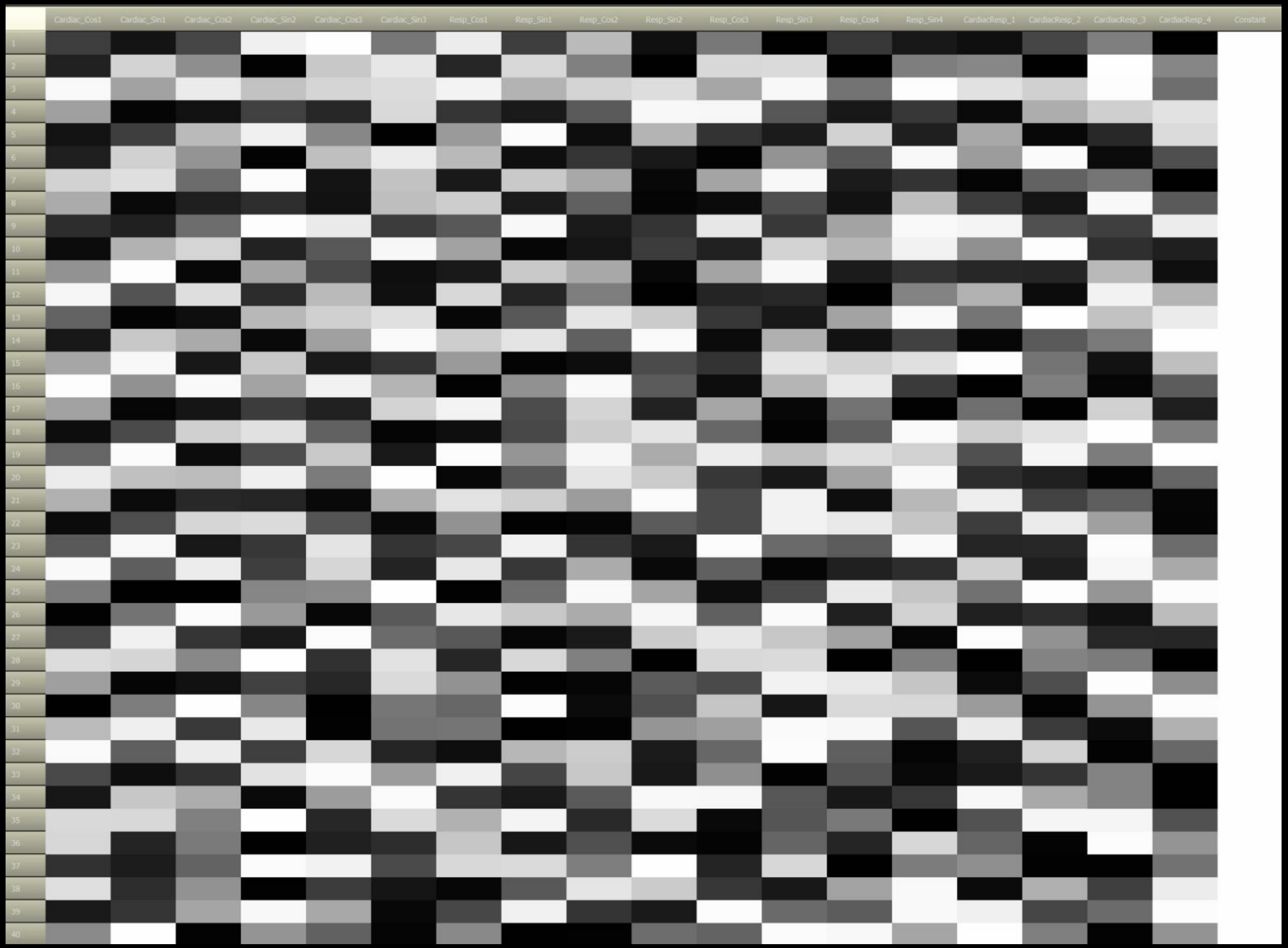
9. *_resp_RETROICOR.sdm
   - Respiratory RETROICOR predictors
   - Default number of respiratory harmonics (N4) based on Harvey et al., 2008 (brainstem imaging)



Output Files (10)

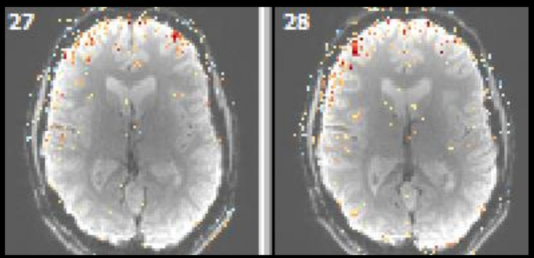
10. *_pulseresp_RETROICOR.sdm
    - The joint cardiac (N3) and respiratory (N4) RETROICOR predictors together with one multiplicative term (N1)
        - cos(cardiac_phase + resp_phase)
        - sin(cardiac_phase + resp_phase)
        - cos(cardiac_phase - resp_phase)
        - sin(cardiac_phase - resp_phase)
    - based on Harvey et al., 2008 (brainstem imaging)

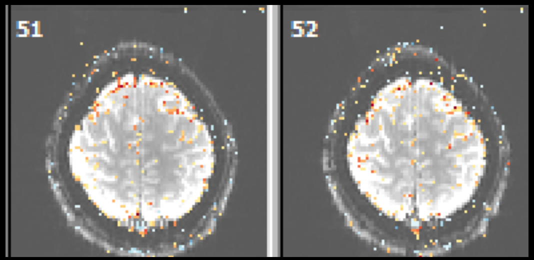


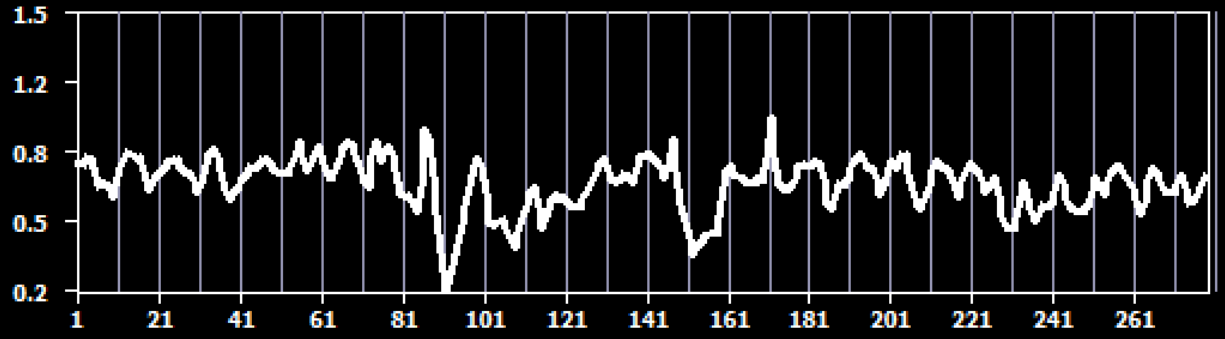


Output Files (11 & 12)

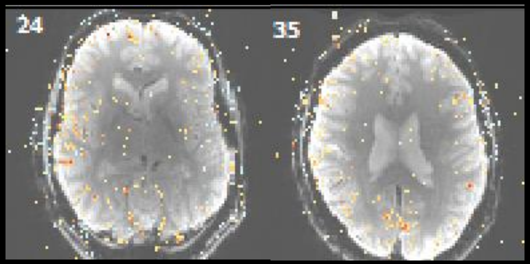
11. *_BR.sdm
    - Breathing rate (BR), expressed in breaths per minute
    - Rescaled by maximum of BR and sampled at t = 0 of each TR

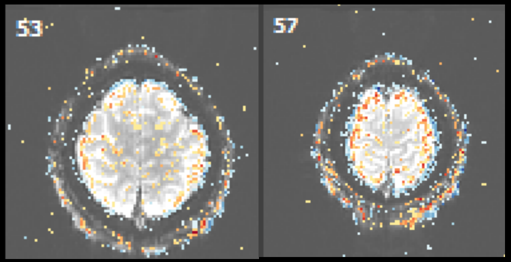


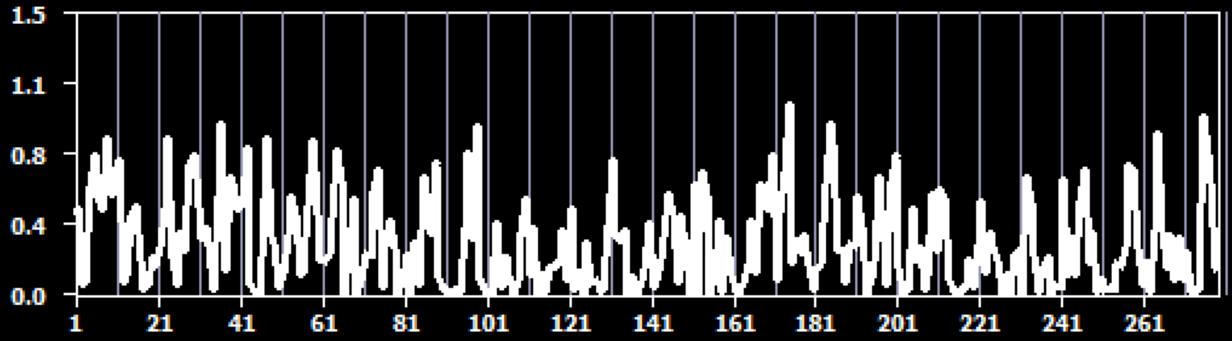




12. *_RF.sdm
    - Respiratory flow, as absolute flow of inhalation and exhalation
    - rescaled by maximum of RF and sampled at each TR (Kassinopoulos & Mitsis, 2019)

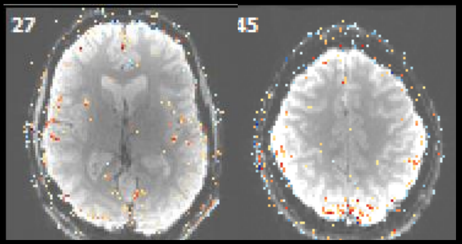


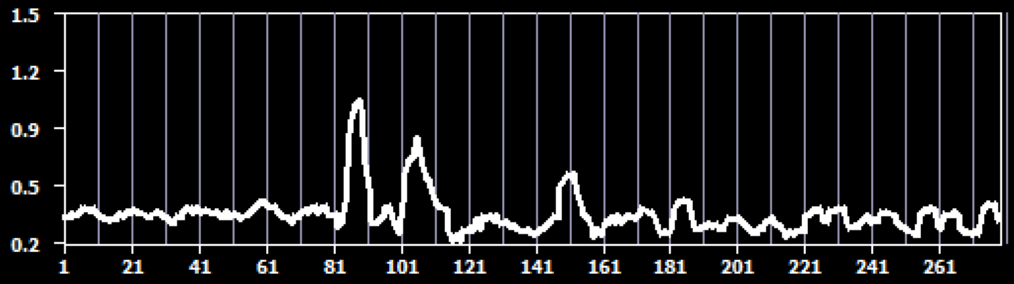




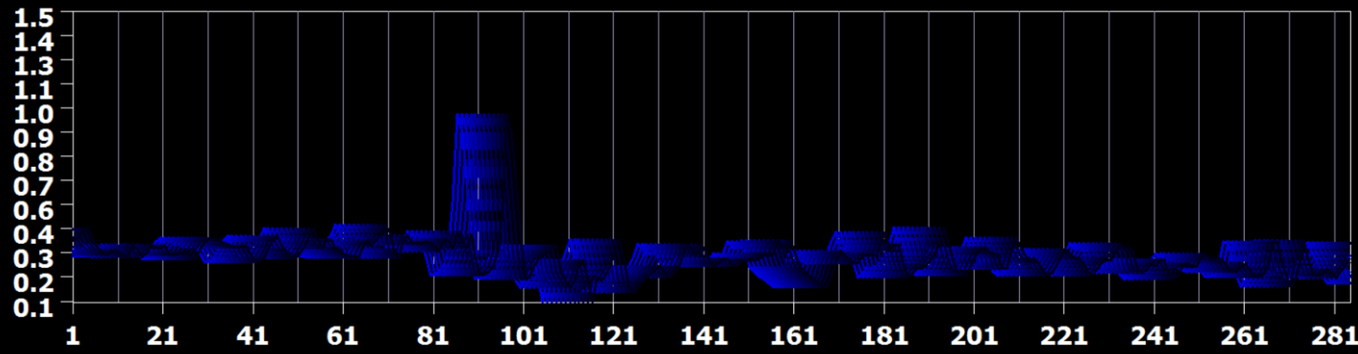
Output Files (13 & 14 & 15)

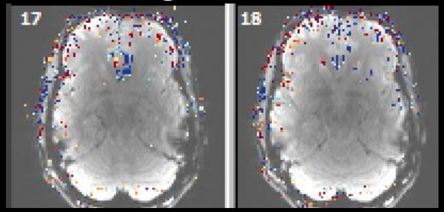
13. *_ENV.sdm (Power et al., 2020)
    - Windowed envelope of respiratory signal over 10 seconds
    - Rescaled by maximum of ENV and sampled at t = 0 of each TR



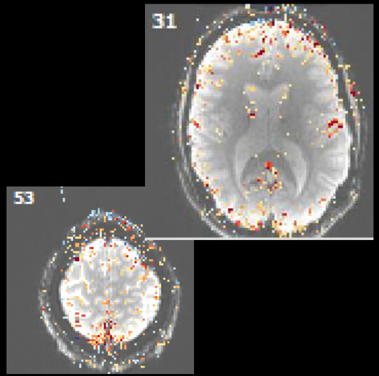


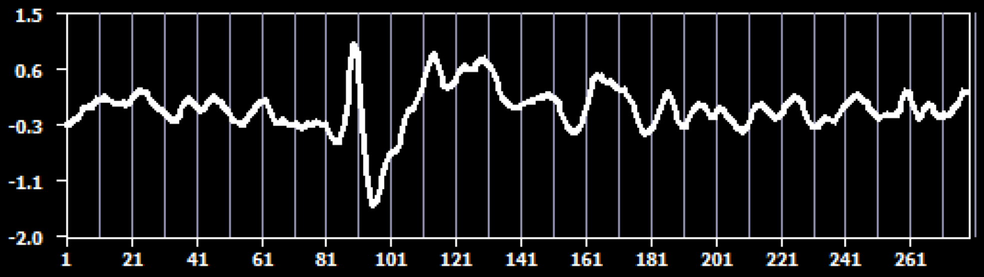
14. *_RVT.sdm (Birn et al., 2006)
    - Respiratory Volume per Time - change in breath amplitude over a breath cycle
    - Rescaled by maximum of RVT and sampled at t = 0 of each TR
    - Time-shifted versions, default: -2:2:20 seconds (Jo et al., 2010) to capture time-varying effects of respiration changes on fMRI signal





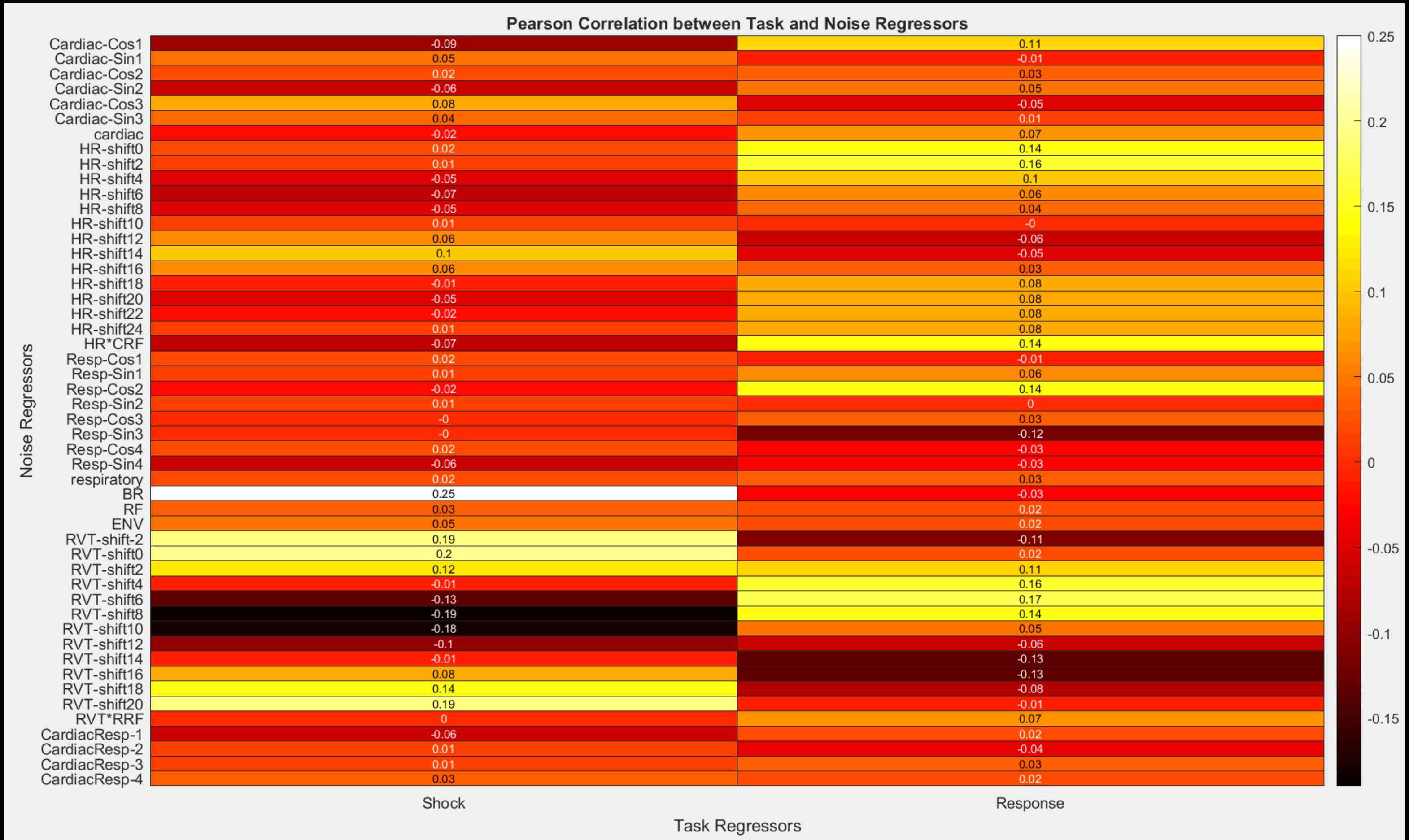
15. *_RVTRRF.sdm (Birn et al., 2008)
    - Respiratory Volume per Time regressor convolved with the respiratory response function (RRF)
    - Final regressor detrended and rescaled by maximum





Output Files (16)

16. _TaskNoiseCorr.png & *_TaskNoiseCorr.fig
    - Only available when Task Design Matrix was provided by user
    - Pearson linear correlation coefficient between all physiological regressors and task regressors and the corresponding p-value for testing rho ≠ 0
    - If correlation is significant a warning message is printed:
      "Warning: Significant correlation (rho = 0.2523, pval= 0) between *Name Task Regressor* and *Name Physiological Regressor*"



Computation of Heart Rate and Breathing Rate per Stimulus Protocol Condition

Extract_HR_BR_ForPRT.m & ReadPRT.m

ReadPRT.m - Output

1. PRTfilename_prt.mat
2. Figure with Experimental Protocol

prt

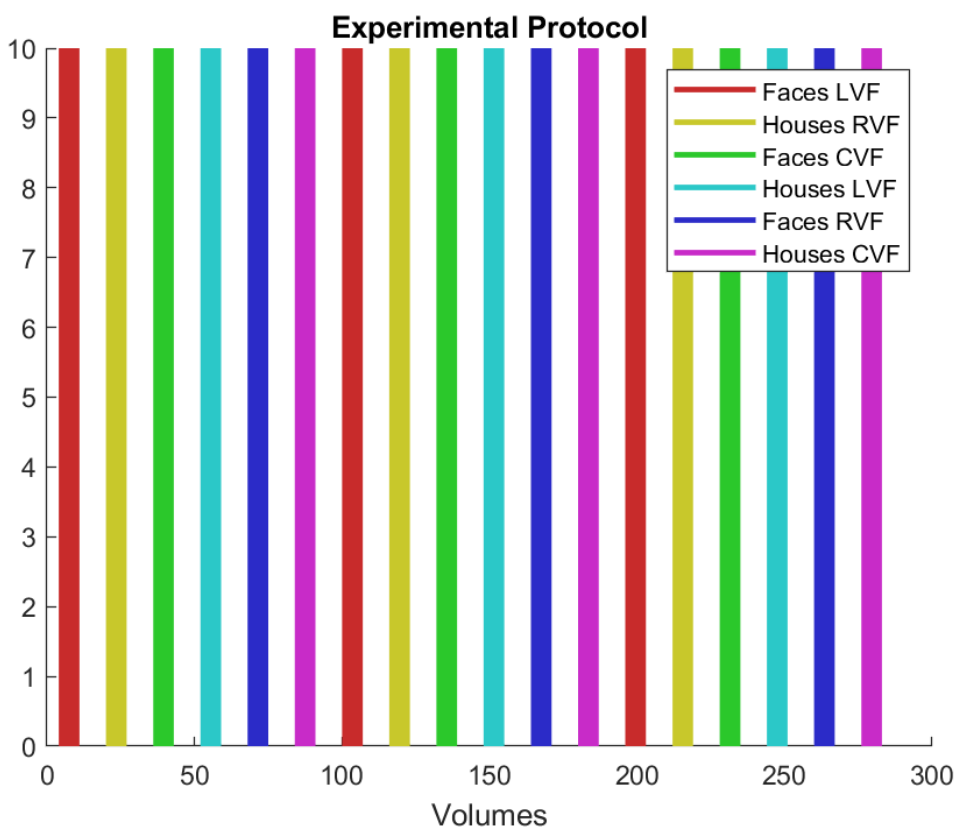
1x1 struct with 6 fields

Field	Value
prtfilename	'sub-01_ses-04_task-blocked_run-1_bold.prt'
prtfiledate	'04-Jul-2019 11:47:34'
resolution	'Volumes'
NoCond	6
Weights	[ ]
Cond	1x6 struct

prt.Cond

prt.Cond

Fields	CondNam	CondIntervals	CondColors	CondOnOffsets
1	'Faces_LVF'	3	[200,43,43]	[4,11;100,107;196,203]
2	'Houses_RVF'	3	[200,200,43]	[20,27;116,123;212,219]
3	'Faces_CVF'	3	[43,200,43]	[36,43;132,139;228,235]
4	'Houses_LVF'	3	[43,200,200]	[52,59;148,155;244,251]
5	'Faces_RVF'	3	[43,43,200]	[68,75;164,171;260,267]
6	'Houses_CVF'	3	[200,43,200]	[84,91;180,187;276,283]



Extract_HR_BR_ForPRT.m (1)
Input and Output

1. Input:
   - Output matlab structure from the script CreatePhysioPredictors_BIDS.m:
     *_cardiacrespiratory.mat OR *_cardiac.mat OR *_respiratory.mat
   - PRT file (via the script ReadPRT.m)

2. Output:
   - Updated physio structure: original mat file name & _inclProtocolInfo.mat

physio

1x1 struct with 28 fields

Field	Value
scriptname	'CreatePhysioPredictors_BIDS.m'
scriptversiondate	'11-Nov-2021 14:50:13'
currentdate	1x1 datetime
Hz	400
startsec	-25.5670
colheader	1x3 cell
data	1x1 cell
NoOfTriggerIntervals	9312
TR	2000
NoVols	291
NoSlices	64
SliceTimingTableSize	64
SliceTable	64x1 double
SliceTimes	32x1 double
time	1x1 cell
PPGpeaks_ind	1x625 double
PPGpeaks_loc	1x625 double
hbi_rmssd	261.4531
HRmean	62.3975
HRstd	8.8538
Regressors	1x1 struct
RESPpeaks_ind	1x121 double
RESPpeaks_loc	1x121 double
BRmean	12.0767
BRstd	1.7814
Task	1x1 struct
TaskNoiseCorr	1x1 struct
prt	1x1 struct

physio.prt

physio.prt

Field	Value
prtfilename	'sub-01_ses-04_task-blocked_run-1_bold.prt'
prtfiledate	'04-Jul-2019 11:47:34'
resolution	'Volumes'
NoCond	6
Weights	[]
Cond	1x6 struct
scriptname	'Extract_HR_BR_ForPRT.m'
scriptdate	'11-Nov-2021 15:14:58'
currentdate	1x1 datetime

physio.prt.Cond

physio.prt.Cond

Fields	CondName	CondInterval:	CondColors	CondOnOffsets	PPGPeak:	PulsePeakTimeDiffVec	MeanHR	StdHR	RespPeak:	RespPeakTimeDiffVec	MeanBR	StdBR
1	'Faces_LVF'	3	[200,43,43]	[4,11;100,107;19...	1x3 struct	1x47 double	63.7394	8.0481	1x3 struct	[6.2625e+03,4.8350e+...	12.6584	1.4318
2	'Houses_RVF'	3	[200,200,43]	[20,27;116,123;2...	1x3 struct	1x47 double	62.7605	7.9920	1x3 struct	[4.5375e+03,3.9625e+...	13.0527	1.9368
3	'Faces_CVF'	3	[43,200,43]	[36,43;132,139;2...	1x3 struct	1x49 double	66.4075	8.8817	1x3 struct	[5.1350e+03,4.3200e+...	12.6534	1.5907
4	'Houses_LVF'	3	[43,200,200]	[52,59;148,155;2...	1x3 struct	1x48 double	65.3213	9.2894	1x3 struct	[4535,4.5425e+03,437...	13.1392	0.9612
5	'Faces_RVF'	3	[43,43,200]	[68,75;164,171;2...	1x3 struct	1x46 double	61.9379	8.3976	1x3 struct	[4.3850e+03,4095,4.55...	14.1680	0.5949
6	'Houses_CVF'	3	[200,43,200]	[84,91;180,187;2...	1x3 struct	1x45 double	62.9726	12.2126	1x3 struct	[7640,4185,4.0625e+0...	10.6180	3.5969
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Extract_HR_BR_ForPRT.m (2)
Script Description

1. If the protocol is defined in Volumes, all condition on- & offsets will be transformed to msec resolution to compare them to the peak times defined in msec
2. saves the script name, the date the script was changed last as well as the current date in the output file
3. find all peaks within each condition interval and save these identified peak times per interval in the prt structure
    1. Case 1: 2 or more peaks were identified in condition interval: ✔
    2. Case 2: no peaks identified in condition interval: take closest peak before onset & closest peak after condition offset
    3. Case 3: only 1 peak identified in condition interval: take closest peak in time outside condition interval irrespective of before onset or after condition offset
4. compute time differences between consecutive peaks in condition intervals
5. compute mean/std heart rate/respiratory rate in each condition interval
6. compute mean/std heart rate/respiratory rate in each condition

Overview Literature

- How to Monitor Physiological Data during fMRI:
  - Bulte, D., & Wartolowska, K. (2017). Monitoring cardiac and respiratory physiology during FMRI. *NeuroImage*, *154*, 81–91. https://doi.org/10.1016/j.neuroimage.2016.12.001
- Nice Overview Work of Cleaning Methods:
  - Caballero-Gaudes, C., & Reynolds, R. C. (2017). Methods for cleaning the BOLD fMRI signal. NeuroImage, 154, 128–149. https://doi.org/10.1016/J.NEUROIMAGE.2016.12.018
  - Murphy, K., Birn, R. M., & Bandettini, P. A. (2013). Resting-state fMRI confounds and cleanup. NeuroImage, 80, 349–359. https://doi.org/10.1016/J.NEUROIMAGE.2013.04.001
- Early Influential Papers Describing the Most Common Cleaning Methods (Based on External Recordings):
  - RETROICOR: Glover, G. H., Li, T.-Q., & Ress, D. (2000). Image-based method for retrospective correction of physiological motion effects in fMRI: RETROICOR. *Magnetic Resonance in Medicine*, *44*(1), 162–167. https://doi.org/10.1002/1522-2594(200007)44:1<162::AID-MRM23>3.0.CO;2-E
  - Respiration Volume per Time, RVT: Birn, R. M., Diamond, J. B., Smith, M. A., & Bandettini, P. A. (2006). Separating respiratory-variation-related fluctuations from neuronal-activity-related fluctuations in fMRI. NeuroImage, 31(4), 1536–1548. https://doi.org/10.1016/j.neuroimage.2006.02.048
  - Respiratory Response Function: Birn, R. M., Smith, M. A., Jones, T. B., & Bandettini, P. A. (2008). The respiration response function: the temporal dynamics of fMRI signal fluctuations related to changes in respiration. NeuroImage, 40(2), 644–654. https://doi.org/10.1016/j.neuroimage.2007.11.059
  - Cardiac Response Function: Chang, C., Cunningham, J. P., & Glover, G. H. (2009). Influence of heart rate on the BOLD signal: the cardiac response function. NeuroImage, 44(3), 857–869. https://doi.org/10.1016/j.neuroimage.2008.09.029
- Other Important Publications:
  - The PhysIO Toolbox from Zurich: Kasper, L., Bollmann, S., Diaconescu, A. O., Hutton, C., Heinzle, J., Iglesias, S., … Stephan, K. E. (2017). The PhysIO Toolbox for Modeling Physiological Noise in fMRI Data. Journal of Neuroscience Methods, 276, 56–72. https://doi.org/10.1016/J.JNEUMETH.2016.10.019
  - Physiological Noise at 7T: Hutton, C., Josephs, O., Stadler, J., Featherstone, E., Reid, A., Speck, O., … Weiskopf, N. (2011). The impact of physiological noise correction on fMRI at 7 T. NeuroImage, 57(1), 101–112. https://doi.org/10.1016/j.neuroimage.2011.04.018
  - Noise Contributions at 7T: Bianciardi, M., Fukunaga, M., van Gelderen, P., Horovitz, S. G., de Zwart, J. A., Shmueli, K., & Duyn, J. H. (2009). Sources of functional magnetic resonance imaging signal fluctuations in the human brain at rest: a 7 T study. Magnetic Resonance Imaging, 27(8), 1019–1029. https://doi.org/10.1016/J.MRI.2009.02.004
  - Order of Preprocessing: Jones, T. B., Bandettini, P. A., & Birn, R. M. (2008). Integration of motion correction and physiological noise regression in fMRI. NeuroImage, 42(2), 582–590. https://doi.org/10.1016/j.neuroimage.2008.05.019
    Jo, H. J., Gotts, S. J., Reynolds, R. C., Bandettini, P. A., Martin, A., Cox, R. W., & Saad, Z. S. (2013). Effective preprocessing procedures virtually eliminate distance-dependent motion artifacts in resting state FMRI. *Journal of Applied Mathematics*, *2013*. https://doi.org/10.1155/2013/935154
  - Comparison of Respiratory Measures: Power, J. D., Lynch, C. J., Dubin, M. J., Silver, B. M., Martin, A., & Jones, R. M. (2020). Characteristics of respiratory measures in young adults scanned at rest, including systematic changes and “missed” deep breaths. NeuroImage, 204, 116234. https://doi.org/10.1016/j.neuroimage.2019.116234
  - Comparison of Different Physiological Response Functions: Kassinopoulos, M., & Mitsis, G. D. (2019). Identification of physiological response functions to correct for fluctuations in resting-state fMRI related to heart rate and respiration. NeuroImage, 202, 116150. https://doi.org/10.1016/j.neuroimage.2019.116150
  - Time-shifted Cardiac Rate Regressors: Shmueli, K., van Gelderen, P., de Zwart, J. A., Horovitz, S. G., Fukunaga, M., Jansma, J. M., & Duyn, J. H. (2007). Low-frequency fluctuations in the cardiac rate as a source of variance in the resting-state fMRI BOLD signal. NeuroImage, 38(2), 306–320. https://doi.org/10.1016/j.neuroimage.2007.07.037