

CHAP: Open-Source Software for Processing and Analyzing Pupillometry Data

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Abstract

Pupil dilation is an effective indicator of cognitive and affective processes. While there are several eye-tracker systems in the market that provide effective solutions for pupil dilation measurement, there is a lack of tools for processing and analyzing the data provided by these systems. For this reason, we developed CHAP - open source software written in MATLAB. This software provides a user-friendly interface (graphical user interface) for processing and analyzing pupillometry data. Our software creates uniform conventions for the pre-processing and analysis of pupillometry data, and provides a quick and easy-to-implement tool for researchers interested in pupillometry. To download CHAP or join our mailing list, please visit CHAP's website: <http://in.bgu.ac.il/en/Labs/CNL/chap>.

Keywords: Pupillometry, GUI, Open-Source Code, Bayesian Analysis, MATLAB

Pupillometry (measurement of changes in pupil size) is an effective indicator of various perceptual, cognitive and affective processes (for reviews see Mathôt, 2018; van der Wel & van Steenbergen, 2018). Pupil size is used in studies examining attentional processes (Breedem, Siegle, Norr, Gordon, & Vaidya, 2017; Geva, Zivan, Warsha, & Olchik, 2013; van Steenbergen & Band, 2013), mental workload (Beatty, 1982; Hess & Polt, 1964; Kahneman & Beatty, 1966; Klingner, Tversky, & Hanrahan, 2011), surprise (Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015; Preuschoff, 't Hart, & Einhäuser, 2011), memory (Beatty & Kahneman, 1966; Goldinger & Papesh, 2012; Otero, Weekes, & Hutton, 2011), and decision making (Einhäuser, Koch, & Carter, 2010; Murphy, Vandekerckhove, & Nieuwenhuis, 2014). Pupil size also reflects high-order visual processing (Einhäuser, Stout, Koch, & Carter, 2008; Kloosterman et al., 2015; Kuchinke, Vö, Hofmann, & Jacobs, 2007; Naber & Nakayama, 2013), and movement preparation (Wang, Brien, & Munoz, 2015; Wang, McInnis, Brien, Pari, & Munoz, 2016). Moreover, pupil size is commonly used as an indicator of arousal and affective processing (Bradley, Miccoli, Escrig, & Lang, 2008; Cohen, Moyal, & Henik, 2015; Hess & Polt, 1960; Partala & Surakka, 2003; Siegle, Steinhauer, Carter, Ramel, & Thase, 2003; Unsworth & Robison, 2017; van Steenbergen, Band, & Hommel, 2011). Pupillometry (mainly pupil light reflex) is also frequently used in ophthalmology studies assessing the physiology of pupil dynamics, as well as changes to pupil size due to diseases such as multiple sclerosis and diabetes (Barbur, Harlow, & Sahraie, 2007; Binda et al., 2017; Feigl et al., 2012; Kostic et al., 2016; McDougal & Gamlin, 2010; Phillips, Szabadi, & Bradshaw, 2001; Wilhelm, Wilhelm, Moro, & Barbur, 2002).

Researchers who are interested in pupillometry use eye-tracking devices (e.g., EyeLink, Tobii, Ergoneers and Mangold), which provide information on eye-movements as well as pupil size. While there are open-source tools for the processing of the eye movement data recorded in these devices (Li, 2017; Sogo, 2013; Zhegallo & Marmalyuk, 2015), there is

a lack of tools for processing and analyzing pupillometry data.

Some of the current eye-tracker companies offer basic tools for processing pupillometry data (e.g., Data Viewer by SR-Research, Tobii Pro Lab by Tobii, etc.), but these tools follow different conventions and include only basic processing of the data. For example, these tools do not correct for blinks or allow for a time-course visualization of the data. While there have been some attempts to provide guidelines and scripts for the pre-processing of pupil size data (Kret & Sjak-Shie, 2018; Mathôt, Fabius, Van Heusden, & Van der Stigchel, 2018), these works do not offer researchers tools for advanced processing and analyses.

For this reason, we developed CHAP (Cohen and Hershman Analysis Pupil) - open source software written in MATLAB. This software provides a user-friendly interface (graphical user interface - GUI) for processing and analyzing pupillometry data. The software receives input of a standard data file from common eye-trackers such as EyeLink (*edf* file), Tobii, ASL (Applied Science Laboratories) or Eye-tribe (*csv* file) and provides both pre-processing and analysis of the data. Our software aims to create uniform conventions for the pre-processing and analysis of pupillometry data, and to offer a quick and easy-to-implement tool for researchers interested in pupillometry.

CHAP's Input

CHAP receives input of a standard data file from various eye-trackers. It receives input from EyeLink (*edf* file), Eye Tribe (both *txt* and *csv* files; see Appendix A for an example), Tobii and ASL eye-trackers (*csv* files; see Appendix A and B for examples). CHAP also supports data files from other eye-tracker devices, as long as they have a specific format (*dat* files; see Appendix B for an example). These input files (*edf*, *csv*, *txt*, or *dat* files) include data on pupil size, as well as information the user entered when programming the experiment (e.g., trial number, condition). Various software programs, such as E-Prime (application software package; Psychology Software Tools, 2001), MATLAB, and

Experiment Builder (SR-Research program provided by EyeLink), can be used to build pupillometry experiments and their use depends on the eye-tracker and on specific task requirements. For processing EyeLink data files (*edf*), CHAP uses EDFMEX (Beta Version 0.9; SR Research, Ontario, Canada) software and EDFMAT (Version 1.6; Adrian Etter Marc Biedermann, University of Zurich) software that read the EyeLink data files and transform them into a MATLAB structure using the EyeLink *edf* Application Programming Interface (API). For processing Eye Tribe data files (i.e., *txt* files resulting from the streamed data of the Eye Tribe interface), python should be installed. Other output files, such as files created by PyGaze (Dalmaijer, Mathôt, & Van der Stigchel, 2014) or PsychoPy (Peirce, 2007) can be converted to *dat* and *csv* files (see Appendix B). For processing input files in a *dat* and *csv* format, CHAP does not require any additional packages.

Running CHAP

After installing CHAP (see Appendix C for installing instructions), the user should write *chap* on MATLAB's command windows or run the main file *chap.m* from the software directory. Then, in order to process and analyze a new data file, the user should click on the *new project* button on the main GUI (see Fig. 1). Next, the user will be asked to choose a data file as follow: for EyeLink data, the file extension should be *edf* (the standard output file of EyeLink, e.g., *sub01.edf*); for Eye Tribe data, the file extension should be *txt* (the standard output file of Eye Tribe, e.g., *sub01.txt*); for ASL data the file extension should be *asl* (a *csv* file renamed with the *asl* extension, e.g., *sub01.asl*); and for Tobii data the extension should be *tbi* (*csv* file renamed with the *tbi* extension, e.g., *sub01.tbi*).

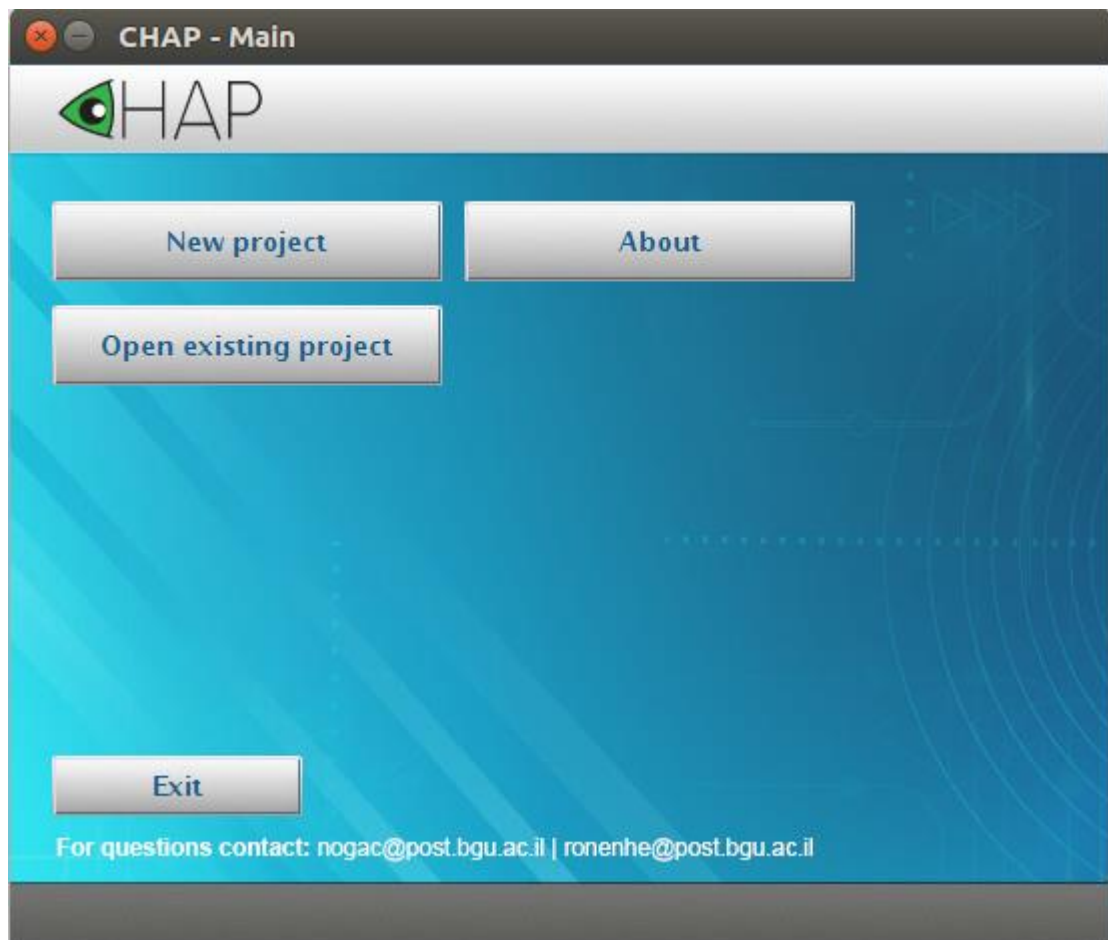


Figure 1. A screenshot of the main GUI of CHAP. This window allows the user to process a new data file (by clicking on *New project*) or to open an existing (already preprocessed) data file (by clicking on *Open existing project*).

Loading, Cleaning and Compressing Files

After CHAP loads the data file and converts it to a mat file, it keeps relevant measures (pupil size and X & Y positions of the pupil) and removes irrelevant information saved by the eye-tracking system, such as indications of fixations and saccades. After this cleaning, CHAP processes the data (see below) and creates a file with the extension *chp* (e.g., *sub01.chp*). This CHAP file can later be loaded by clicking on the *Open existing project* button on the main GUI (Fig. 1). This compression of the data, which results in a *chp* file that is approximately 10 times smaller than the original data file, allows fast and efficient processing of the data.

Trials, Variables and Events

Pupil size is usually recorded in experiments that consist of different trial types.

CHAP uses user-defined information in order to split the data into trials, to analyze different events within a trial (e.g., pupil size during stimulus presentation) or to compare different conditions (which we call variables; e.g., congruent vs. incongruent Stroop stimuli).

In order to detect trial onset, CHAP uses EyeLink standards. Namely, CHAP looks for logs with a string in the format: ***TRIALID [trial id]***. This log is created by EyeLink when Experiment Builder is used for programming the task. In case of other software (MATLAB, E-Prime), this log should be defined by the user (see Appendix A for examples). For trial offset, CHAP uses logs with a string that is either ***TRIAL_RESULT 0*** (the EyeLink standard format) or ***TRIAL_END*** (see Appendix A for examples). In the case where the user did not send a log that defines a trial's offset, CHAP will use the onset of the subsequent trial as offset of the current trial.

CHAP also detects user-defined variables and events (up to 64 of each). These variables and events are defined by the researcher when building his/her experiments and should be logged into the data file. Variables should indicate conditions (e.g., congruency in a Stroop task, valance in a study assessing emotional processing), as well as other information about the trial (e.g., block number, accuracy). Events should indicate the relevant factors that occur during a trial (e.g., fixation, stimulus, inter-trial interval).

CHAP recognizes the variables using logs with text strings that appear in the data file, according to EyeLink standards (***!V trial_var [variable name] [variable value]***). For example, a possible string could be ***!V trial_var congruency congruent***. In this example, the variable name is congruency and the value is congruent. CHAP also supports other types of variable formats by reading an external *csv* file created by the user (see Appendix D). This file should include the variables for each trial (i.e., trial ids, variable names and variable

values). This external file is especially helpful when the values of some of the variables are unknown during data acquisition. This can happen, for example, in a Stroop task in which participants provide a vocal response that is coded to be correct or incorrect only at the end of the experiment. Another example is a memory experiment in which it is unknown during the encoding phase whether the stimulus will be remembered or forgotten. Therefore, CHAP allows the user to add information about trial accuracy or any other relevant information that does not appear in the data file, using an external *csv* file. In the case where the researcher wants to use this option, he/she should create a *csv* file for each participant. This *csv* file should have the same name as the main data file with the addition of a dedicated suffix - *_vars* (e.g., *sub01_vars.csv*). This file should be located in the same folder as the main data file.

CHAP recognizes events using logs that consist of the string ***!E trial_event_var [event name]***. For example, a possible string that indicates the appearance of a stimulus could be ***!E trial_event_var stimulus_onset***. In addition, in contrast to the straightforward approach of logging events at the moment they occur, CHAP also supports the following pattern (that is used in EyeLink): ***[milliseconds before the trial's ending] [event name]***. It means that instead of logging the event's information following the event's onset, the user can send the relevant log at the end of the trial. This approach is useful when using third-party software, such as E-Prime. Similar to supporting the addition of external variables, CHAP also supports the addition of external events. By using dedicated *csv* files, the user can specify events that were not logged into the data file during recording (see Appendix D). These files should be selected manually by the user during the data file loading.

Data Pre-Processing

After CHAP reads the data and converts it to a *chp* file, pupil data (pupil size in pixels or any other units) is pre-processed. Pre-processing includes:

1. Exclusion of outlier samples (Akdoğan, Balci, & van Rijn, 2016; Cohen et al., 2015; Wainstein et al., 2017). CHAP converts pupil size data to z-score values based on the mean and standard deviation (*SD*) calculated for each trial separately. Z-score values above or below a user-defined threshold, as entered in the *Z Outliers* text field in the *data-processing* GUI (see Fig. 2), will be converted to missing (not a number) values (NaN).

2. Blink correction. CHAP searches for blinks (or any other missing values) in the data and reconstructs the pupil size for each trial from the relevant samples using either linear interpolation (Bradley et al., 2008; Cohen et al., 2015; Siegle et al., 2003; Steinhauer, Condray, & Kasperek, 2000) or cubic-spline interpolation¹ (Mathôt, 2013; Mathôt et al., 2018; Smallwood et al., 2011; Wainstein et al., 2017). The user can select the interpolation method in the select list menu that appears in the *data-processing* GUI (see Fig. 2). To find blink onset and offset, CHAP uses a novel algorithm that we have recently developed (Hershman, Henik, & Cohen, 2018) that takes into account the change in pupil size between subsequent samples. The user can see the blink correction by choosing the *View Trials* checkbox in the *data-processing* GUI (see Fig. 2). Accurate correction of blinks is highly important as it prevents artifacts in the data (Hershman et al., 2018).

3. Exclusion of outlier trials (Blaser, Eglington, Carter, & Kaldy, 2014; Cohen et al., 2015; Hershman & Henik, 2018; Nyström, Andersson, Holmqvist, & van de Weijer, 2013; Schmidtke, 2014; Wainstein et al., 2017). CHAP removes trials based on a user-defined percentage of missing pupil observations within a trial (*Missing values (%)* text field in the

¹ Cubic interpolation is less recommended when the data is relatively noisy or when the sampling rate is relatively low (below or equal to 60 Hz)

data-processing GUI; see Fig. 2). Missing observations occur during blinks, head movements, or inability of the eye-tracking system to track the pupil. Trials that contain a high percentage of missing samples should not be used in the analysis (Nyström et al., 2013). We recommend excluding trials with more than 20% missing samples.

4. Exclusion of participants. CHAP excludes participants that do not meet the user-defined criteria for a minimum number of valid trials per conditions (*Min. trials* text field in the *data-processing* GUI; see Fig. 2). If a participant does not reach the user-defined value (e.g., due to low tracking quality the participant has less than 10 valid congruent trials), an error message will appear and the participant will not be included in the analysis.

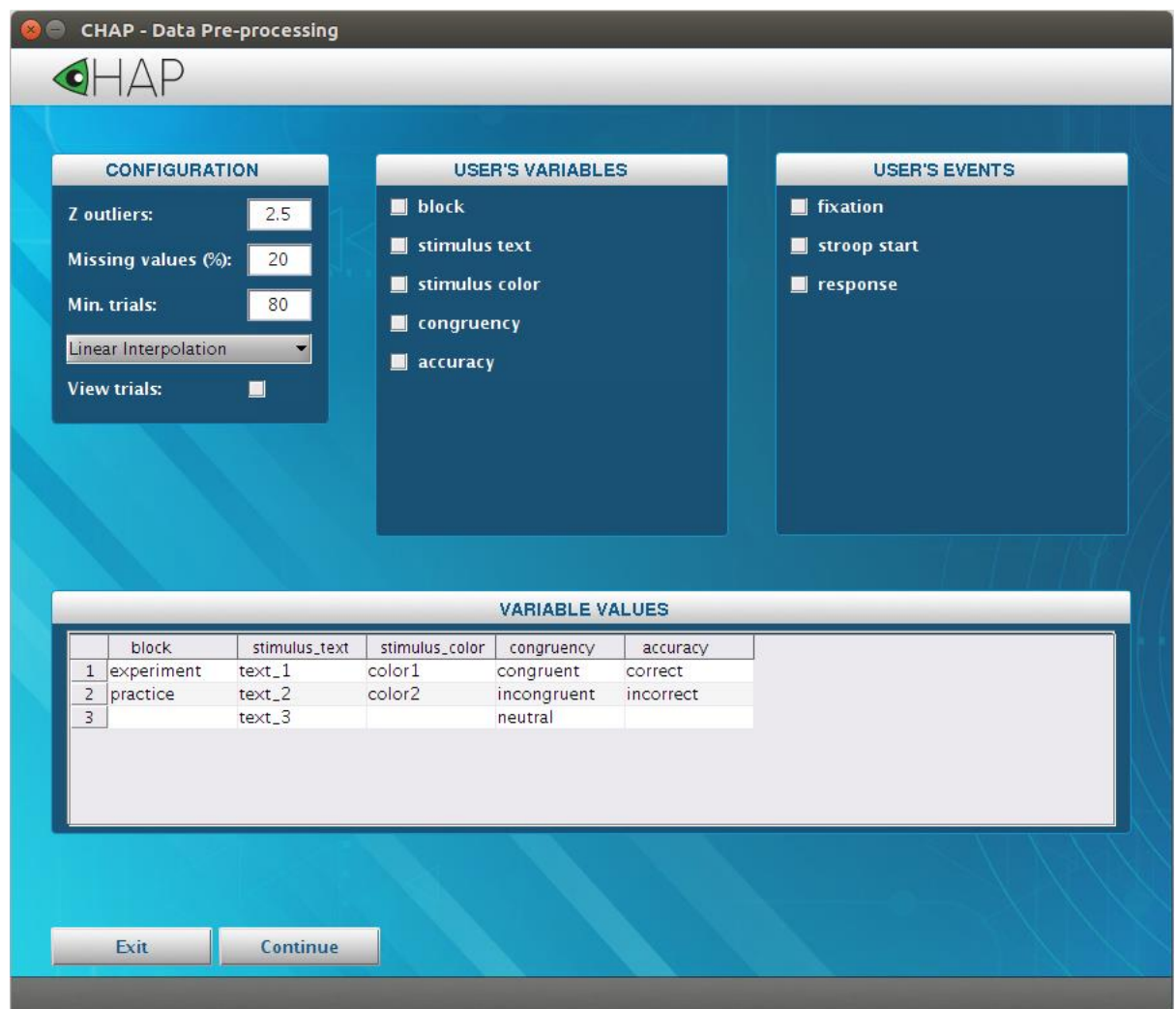


Figure 2. Screenshot of the GUI for data pre-processing. This GUI allows the user to choose

parameters for data exclusion, as well as the relevant variables and events. The variable names and their values (as they appear in the data file) are presented in a dedicated table (*VARIABLE VALUES*).

Selecting Variables and Events

The interface *data-processing* GUI presents a list of the variables and events that were logged during the experiment (see Fig. 2). The user can choose what variables and events he/she wants to analyze. After selecting the parameters for excluding trials and participants and the desired variables and events, the user should click the *Continue* button (see a screenshot in Fig. 2). Then, the *condition-selecting* GUI will be opened. This GUI allows the user to select the desired conditions (up to 7) from a list. The list includes all the possible combinations depending on the selected variables (see an example in Fig 3).

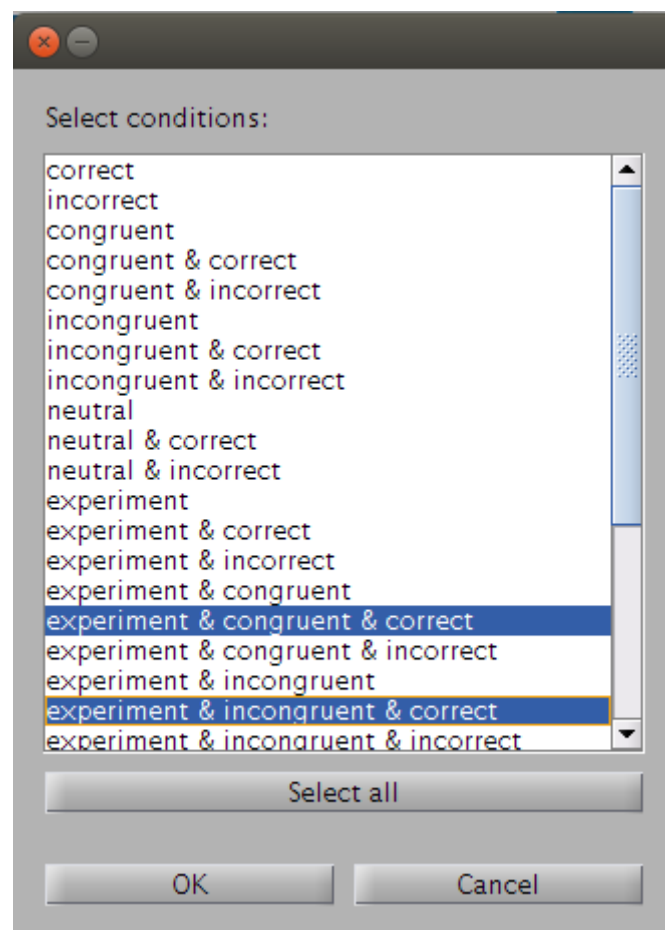


Figure 3. A screenshot of the *condition-selecting* GUI. This GUI allows the user to select the desired conditions for analysis. In this example, the user chose experimental trials

(experiment), with either congruent or incongruent stimuli that were answered correctly.

Time-Course Visualization

After the user selects the relevant variables and events, CHAP presents data for each selected condition (mean pupil size across all valid trials) and indicates the selected events on a dedicated graph (see Fig. 4). By default, the y-axis represents mean pupil size (with the given units from the data file) as a function of time (in milliseconds). Each curve represents a condition (the selected conditions appear in the legend) and the vertical lines represent the mean onset time of each selected event (as selected in the *data pre-processing* GUI). The title (in this case: *20170625a*) represents the participant's id, as defined by the name of the file (in this case: *20170625a.txt*)

For each of the selected conditions, CHAP presents the number of trials that were used to generate the mean, as well as the number of trials that were defined as outliers and therefore were removed from analysis (see Fig. 4). CHAP also presents the mean onset of the selected events relative to the beginning of the trial, as well as the mean offset of each condition.

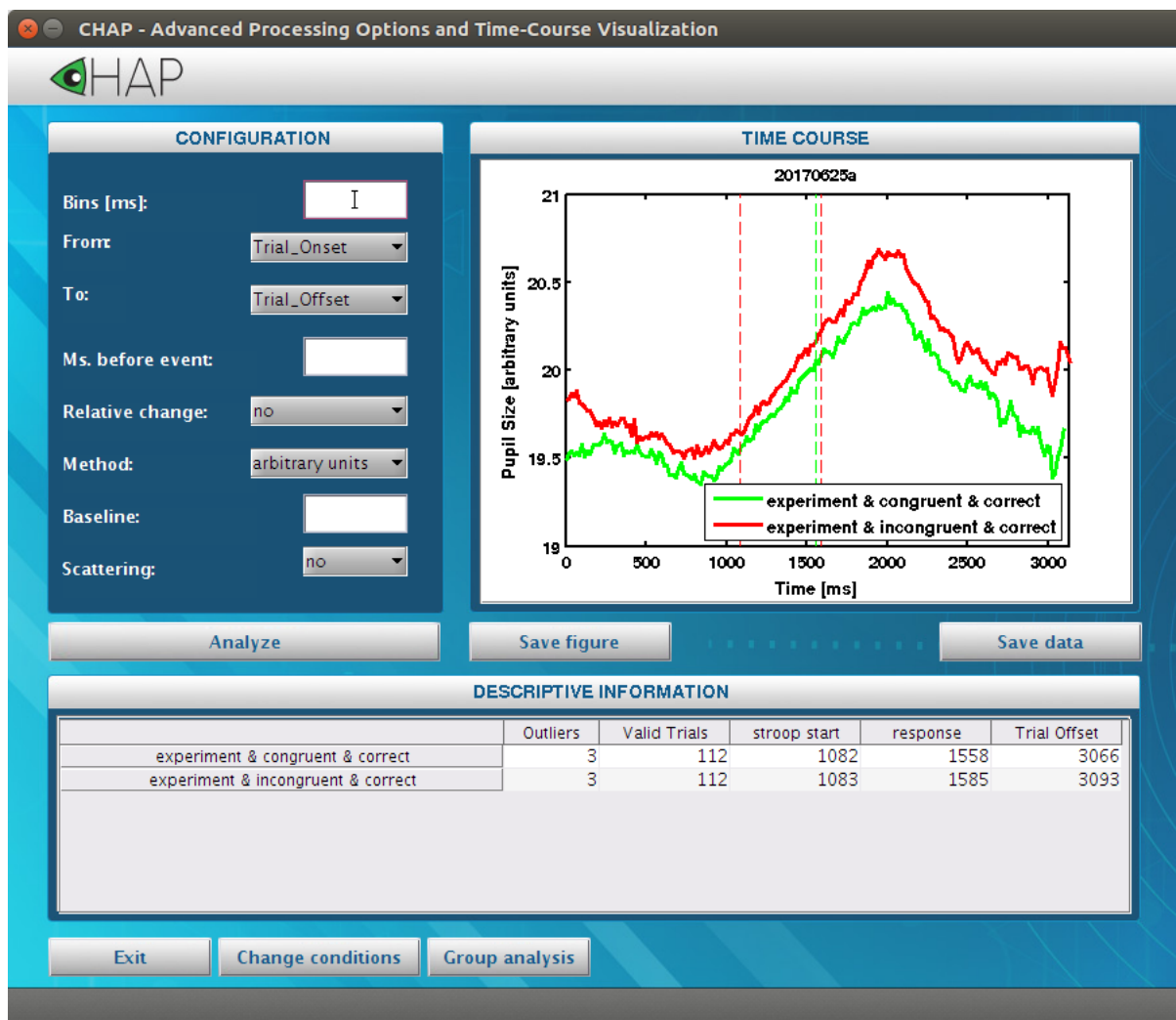


Figure 4. Screenshot of the *advanced processing options and time-course visualization* GUI. This GUI allows the user to define processing parameters and to view a time-course visualization of the data.

Advanced Processing Options

In addition to basic pre-processing of the data (Fig 5a), CHAP supports several advanced analysis features (Fig 5b-5g). These features can be selected by the user on the *advanced processing options and time-course visualization* GUI (see configuration section in Fig. 4) and are outlined below.

Bins. Down-sampling (reducing the sampling rate) is performed by averaging adjacent samples of an overall X (user-defined) milliseconds. Specifically, CHAP divides the

data to chunks that include samples with total duration of X ms each. Then, CHAP calculates the average value for each of these bins (see Fig. 5b for an example). The onset of each bin is defined as the time of the first sample (see Fig. 6 for an example). By using this feature, the user can aggregate the data for analysis or for smoothing purposes (Diede & Bugg, 2017; Kang & Wheatley, 2015; Snell, Mathôt, Mirault, & Grainger, 2018). This option could also be useful in case of comparing data that was collected using different eye-trackers or different sampling rates (Titz, Scholz, & Sedlmeier, 2017), or to correlate between pupil size and another measure such as BOLD (blood-oxygen-level dependent) activity (Murphy, O’Connell, O’Sullivan, Robertson, & Balsters, 2014; Yellin, Berkovich-Ohana, & Malach, 2015).

Time-window. In most psychological experiments, each trial includes several events (e.g., fixation cross, target, inter-trial-interval). CHAP allows the user to select a specific time-window (from one event to another) for analysis (Fig. 5c). When the user uses this feature, the data is aligned to the onset of the first selected event (Kloosterman et al., 2015; Snell et al., 2018; Turi, Burr, & Binda, 2018). This alignment of the data is especially important when the event does not start at a fixed time (e.g., a stimulus appears after 2 seconds in some trials and after 2.5 seconds in other trials). This can happen when stimulus onset is determined by participant response time (that varies from trial to trial), or when a stimulus appears after a variable inter-stimulus-interval (ISI).

Relative change. Instead of using the units recorded by the eye-tracker device (e.g., number of pixels in the case of an EyeLink device), the user can convert the data to a relative change score (Mathôt et al., 2018). The relative change indicates the difference from baseline (i.e., subtractive baseline correction; Binda & Murray, 2015; Binda, Pereverzeva, & Murray, 2014; Steinhauer, Siegle, Condray, & Pless, 2004): $relative = value - baseline$ (Fig. 5d), or

the percent change from baseline (divisive baseline correction; Binda et al., 2014; Kloosterman et al., 2015; Mathôt, van der Linden, Grainger, & Vitu, 2013; Snell et al., 2018):

$$relative_{\%} = 100 \cdot \frac{value}{baseline} \text{ (Fig. 5f).}$$

The baseline is defined by the user as an average of X milliseconds prior to the onset of the first event (Binda et al., 2014; Mathôt et al., 2013; Snell et al., 2018).

Conversion to Z-scores / millimeters. Most eye-trackers provide pupil data in arbitrary units. These units (or values) are dependent on the eye-tracker definitions during recording, the position of the camera, the distance between the camera and the participant, as well as other parameters such as the lighting conditions of the room. Normalization of the data (converting the data to comparable values such as z-score values instead of arbitrary units) makes it possible to analyze and compare participants/experiments whose data was recorded with different conditions.

If the user chooses to convert arbitrary units to z-scores (Cohen et al., 2015; Einhäuser et al., 2008; Kang & Wheatley, 2015; Wainstein et al., 2017), CHAP will calculate the z-score values based on the entire time course of the participant (i.e., the mean and *SD* will be calculated on all valid trials for that participant) (Fig. 5e). Alternatively, the user can choose to convert arbitrary units to millimeters (Binda & Murray, 2015; Binda et al., 2014; Blaser et al., 2014; Siegle, Steinhauer, & Thase, 2004) by recording an artificial pupil of fixed size and providing CHAP its millimeter and arbitrary units sizes. Pupil size is recorded in either diameter or area measurement and CHAP recognizes the right measurement after the data is loaded.

CHAP uses the following equations to get the sizes in millimeters:

In the case of diameter

$$pupil_{diameter}[mm] = pupil_{diameter}[arbitrary_units] \cdot ratio$$

where *ratio* is the ratio between the artificial pupil diameter (*AP*) in millimeters and in pixels described by:

$$ratio = \frac{AP_{diameter}[mm]}{AP_{diameter}[arbitrary_units]}$$

In the case of area

$$pupil_{diameter}[mm] = pupil_{diameter}[arbitrary_units] \cdot ratio$$

$pupil_{diameter}[arbitrary_units]$ is described by:

$$pupil_{diameter}[arbitrary_units] = 2 \sqrt{\frac{pupil_{area}[arbitrary_units]}{\pi}}$$

ratio is the ratio between the artificial pupil diameter (*AP*) in millimeters and in pixels described by:

$$ratio = \frac{AP_{diameter}[mm]}{AP_{diameter}[arbitrary_units]} = \frac{AP_{diameter}[mm]}{2 \sqrt{\frac{AP_{area}[arbitrary_units]}{\pi}}}$$

For the conversion of the data to millimeters, the user should add a *csv* file for each participant with the same name as the main data file with the addition of the suffix - *_mm* (e.g., *sub01_mm.csv*). This file should be located in the same folder as the main data file (see Appendix E).

Scattering. The user can add scattering around the mean for each curve. The scattering is either the standard error or the confidence interval of 95% (Fig. 5g).

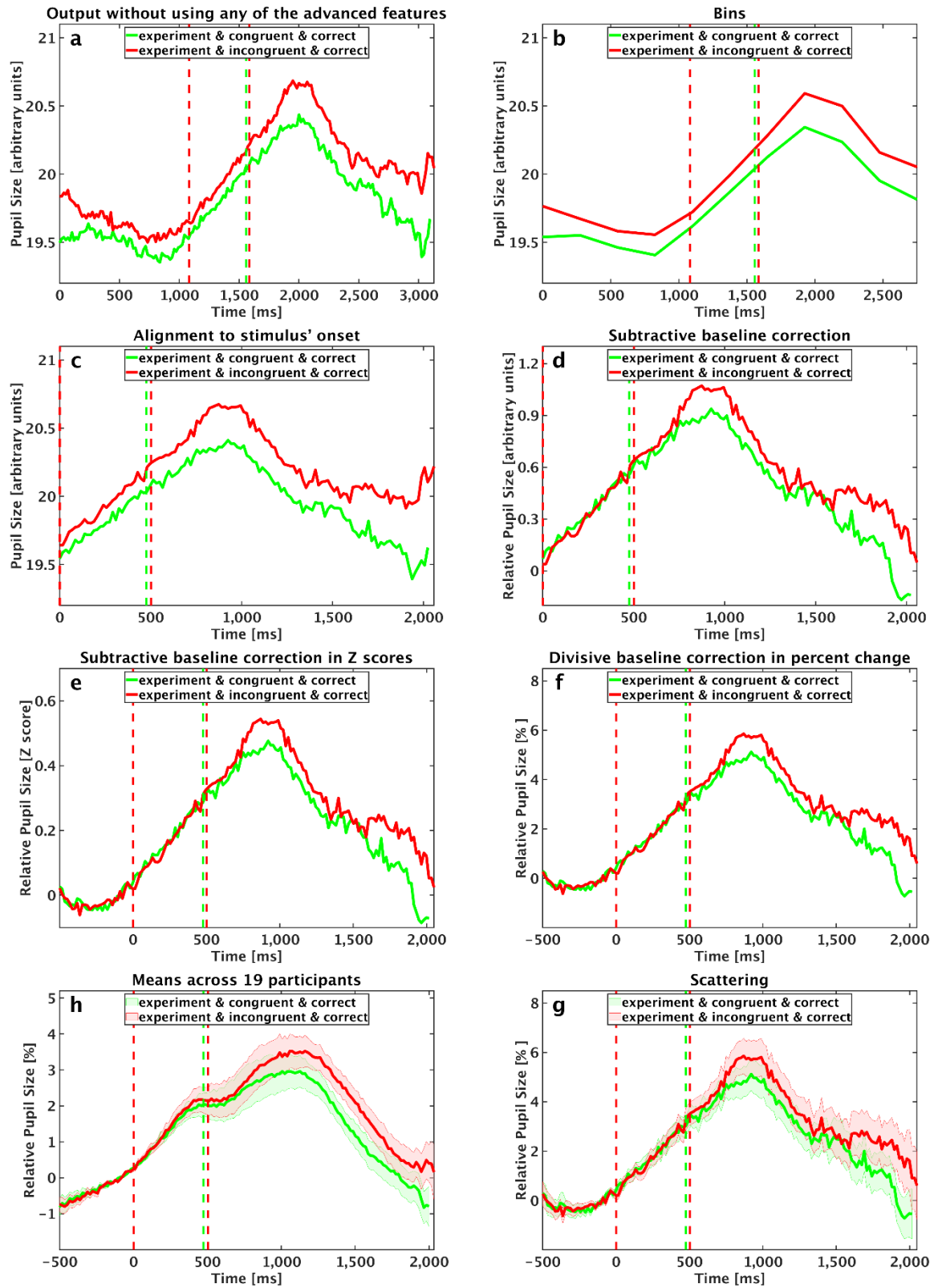


Figure 5. Examples of CHAP's features: Mean pupil size as a function of time in a 2-colors Stroop task run on 19 participants (Exp. 1 in Hershman & Henik, 2018). Participants were instructed to respond to the color of a word and to ignore its meaning. The task consisted of congruent and incongruent trials (e.g., congruent: BLUE, incongruent: BLUE). The red

curves represent correct incongruent experimental trials and the green curves represent correct congruent experimental trials. The vertical lines close to 1,000 ms represent the mean time of the Stroop stimulus onset and the vertical lines close to 1,500 ms represent the mean participant response. Figures (a) – (g) present data of one participant, while figure (h) presents average data across 19 participants. **(a)** Average pupil size across the different conditions without using any of the advanced features. **(b)** Down-sampling the data by using bins of 250 ms. Here, each bin (points on the curves) represents averaging of 15 adjacent samples (as the sampling rate was 60 Hz). **(c)** Data from stimulus onset to the end of the trial. 0 (on the X-axis) represents the stimulus onset and the vertical lines close to 500 ms represent the mean participant response time. **(d)** Aligned data in relative change (subtractive baseline correction - in pixels). **(e)** Aligned data in normalized relative change (subtractive baseline correction). The data was normalized by using z-scores. **(f)** Normalized relative changes (divisive baseline correction in percent) from 500 ms before Stroop stimulus onset until trial offset. **(g)** Normalized relative change (divisive baseline correction in percent) from 500 ms before stimulus onset until trial offset. Here the shades around the curves represent 1 standard error from the mean. **(h)** Group analysis across 19 participants. Normalized relative change (divisive baseline correction in percent) from 500 ms before stimulus onset until trial offset. The shades around the curves represent 1 standard error from the mean. For all figures with a baseline correction, the baseline was an average of 200 ms before Stroop stimulus onset.

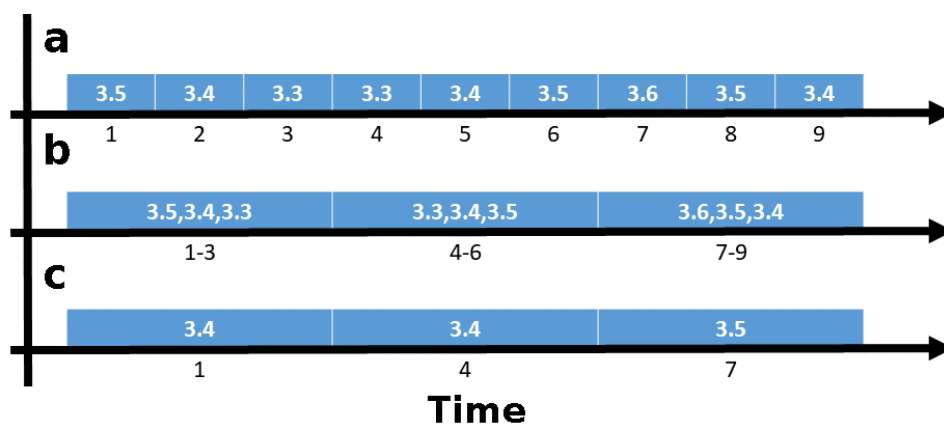


Figure 6. Schematic example of down-sampling using bins. In this examples, sampling rate is 1,000 Hz (1 sample every 1 ms) and each bin is 3 ms (3 samples in this case). **(a)** Pupil data in millimeters for each sample. **(b)** Chunks of 3 samples (corresponds to 3 ms bins). **(c)** Average pupil size for each bin.

Output Files

CHAP saves four types of output file. The presented figure can be saved by the user as a *png* (standard image file) or as a *fig* (standard MATLAB figure file) by clicking on the *save data* button on the *advanced processing options and time-course visualization* GUI (Fig. 4). In addition, the processed data can be saved as a *csv* or a MATLAB file that contains all the data about the relevant variables and events for each participant (by clicking on the *save data* button on the *advanced processing options and time-course visualization* GUI; see Fig. 4).

The *csv* and *mat* files include average pupil size for each condition across all valid trials (see Appendix F). This data could be later used for analysis in external code / third party software. Other information that is saved by CHAP includes participant name (as defined by the data file name), trial number, value for each defined variable, as well as event onset relative to the beginning of the selected time-window (see Appendix F). In addition to mean pupil size, CHAP also provides information about mean pupil size in the first and last bin, and minimum and maximum pupil size value during the selected time-window. CHAP also provides information about the number of eye-blinks and their durations. This information could be useful in studies that are interested in blinks, such as studies assessing startle response (e.g., Graham, 1975) or blink length and eye-blink rate (Monster, Chan, & O'Connor, 1978), a measure known to be correlated with dopamine level (Jongkees & Colzato, 2016; Karson, 1983).

Group Analysis

Once users process one data file, they can run the same configuration for multiple data files (e.g., different participants). This option is available in the *advanced processing options and time-course visualization* GUI (see Fig. 4) by clicking on the *group analysis*

button. The user should select the folder that contains the data files and choose a name for the analysis. Then, output files will be created for each data file and for the mean of all participants (see Fig. 5H for the mean across 19 participants). In addition to these files, CHAP also provides *csv* files that include information about the number of trials that were used in the analysis (*valid_trials.csv*), as well as the number of excluded trials (*outliers.csv*), for each condition for each participants. Moreover, CHAP provides *csv* files that include information about the mean event's onset for each trial for each participant (*all.csv* and *rdm_all.csv*; see Appendix G).

Parameters for Statistical Analysis

CHAP provides the commonly used parameters for analysis such as the mean (Binda et al., 2014; de Gee, Knapen, & Donner, 2014; Hemmati, Johansson, & Magnusson, 2017; Laeng, Ørbo, Holmlund, & Miozzo, 2011), peak amplitude (Binda & Murray, 2015; Hemmati et al., 2017; Hess & Polt, 1964; Schmidtke, 2014), peak latency (Hess & Polt, 1964; Koelewijn, de Kluiver, Shinn-Cunningham, Zekveld, & Kramer, 2015; Laeng et al., 2011; Schmidtke, 2014), dip amplitude (Bitsios, Szabadi, & Bradshaw, 2004; Henderson, Bradley, & Lang, 2014; Steinhauer et al., 2000) and dip latency (Lanting, Strijers, Bos, Faes, & Heimans, 1991; Shah, Kurup, Ralay Ranaivo, Mets-Halgrimson, & Mets, 2018; Steinhauer et al., 2000). These parameters can be selected for a specific time-window or for the entire trial. By selecting the desired time-window (*From* and *To* field on the *statistical analysis* GUI; Fig 7), these parameters will be calculated based on the data within the selected time-window (see table in Fig 7).

Statistical Analysis

CHAP provides two approaches for statistical analysis. CHAP has the option to run a repeated measures analysis of variance (repeated measures ANOVA). The output of this analysis includes the F-value (including degrees of freedom), p-value, η_p^2 and MSE (see table

in Fig 7). In addition to the main effect, CHAP will run a series of orthogonal contrasts and will present them in the same table with the F-value, p-value, and MSE.

In addition to this parametric approach, CHAP also supports a Bayesian approach. Specifically, CHAP can run a Bayesian paired-sample t-test with Cauchy prior width of $r = .707$ for effect size on the alternative hypothesis (Rouder, Morey, Speckman, & Province, 2012). In this analysis, the null hypothesis means that there is no difference between the tested conditions. The Bayesian analysis provides a Bayes factor (Kass & Raftery, 1995) for each condition. This Bayes factor quantifies the evidence in favor of the alternative hypothesis over the null hypothesis. Similar to the output of the parametric analysis, by selecting the Bayesian approach (*approach* button on the *statistical analysis* GUI; Fig 7), CHAP will run and present the output for the Bayesian analysis. The output for each condition includes the t-value, BF_{10} (evidence in favor of the alternative hypothesis), BF_{01} (evidence in favor of the Null hypothesis), Cohen's d and the number of observations.

Temporal Analysis

CHAP also supports temporal analysis of the data (Binda et al., 2014; Einhäuser et al., 2008; Mathôt et al., 2013; Siegle et al., 2003). By using temporal analysis, the user can investigate the temporal differences between conditions across the time course or a selected time-window.

Similar to the analysis described above, CHAP supports both Bayesian and classical approaches (*approach* button on the *statistical analysis* GUI; see Fig. 7). Specifically, CHAP runs a series of paired sample t-tests between each two conditions over the entire selected time-course (Fig. 7) as defined in the *advanced processing options and time-course visualization* GUI.

The output provided by CHAP (presented in a figure and also saved as a *csv* file for each comparison) is a Holm-Bonferroni corrected p-value as a function of time (by using the

classical approach), or Bayes factor (both BF_{10} and BF_{01}) as a function of time (by using the Bayesian approach). In addition to the descriptive information about the Bayes Factor as a function of time (by using the Bayesian approach), CHAP also provides inference information about differences and similarities between conditions.

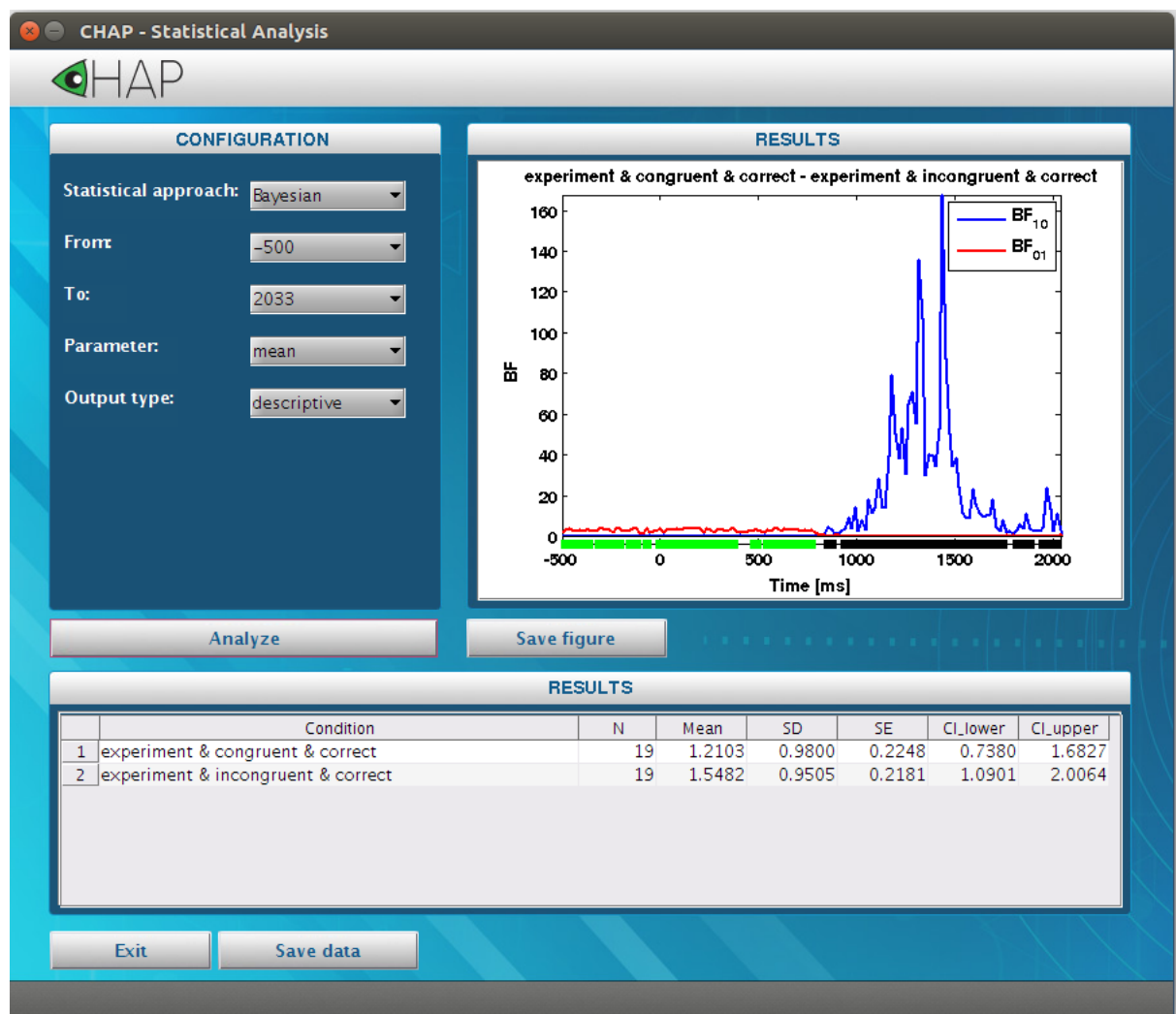


Figure 7. Screenshot of the *statistical analysis* GUI. Here the user can select the approach for the analysis, define a time-window of interest and see both descriptive and inference results. The figure presents the comparison between congruent and incongruent trials across 19 participants. Both BF_{10} (blue curve) and BF_{01} (red curve) are presented as a function of time. The black and green horizontal lines below the curves represent the results of the Bayesian analysis. The black lines represent meaningful differences between conditions and the green lines represent support of no differences between conditions. The Bayes Factor threshold value that CHAP uses (hard-coded) for this analysis is 3 (Jeffreys, 1961). In the current

example, there is a meaningful similarity between conditions from -500 ms to 750 ms, and a meaningful difference between conditions from 1,000 ms to 2,000 ms.

Discussion

In this paper, we presented CHAP - open source software written in MATLAB for processing and analyzing pupillometry data. CHAP provides a user-friendly tool for researchers who are interested in pre-processing and analysis of pupillometry data. CHAP supports data coming from a wide range of eye-tracker devices and includes, what we believe, the most up-to-date and cutting-edge processing and analysis options. By using well-established approaches, CHAP makes working with pupillometry data easier and provides efficient solutions for pre-processing, analysis and visualization of the data. Besides that, by introducing CHAP we suggest uniform conventions for the pre-processing and analysis of pupillometry data. CHAP's user-interface makes it an easy-to-implement tool, for both experienced MATLAB users as well as for researchers who do not have any experience with programming. CHAP can be easily installed on Windows, Linux and Mac operation systems (see Appendix C for instructions) and experienced users can also modify the code if they wish to (as the MATLAB script is available after installation).

There are several challenges that should be addressed in future work. First, as pupil size is influenced by gaze position (Brisson et al., 2013; Gagli, Hawelka, & Hutzler, 2011), this data should be used to exclude trials with large eye movements or to correct for pupil size. We plan to develop a correction for measurement of pupil changes during eye movements. Such corrections will be inserted in future CHAP versions. Second, currently CHAP supports only a one-way ANOVA and t-tests. In the future, we plan to add more options for data analyses. In addition, CHAP currently supports only a within-group analysis. We plan to add options for the analysis of between-groups effects. Finally, we plan to create a Python version of CHAP so that it can be used by users who do not have MATLAB.

To summarize, this paper presented CHAP, a tool for processing and analyzing pupillometry data. CHAP is already being used by several groups and it is our hope that more researchers will use it. To download CHAP or join our mailing list please visit CHAP's website: <http://in.bgu.ac.il/en/Labs/CNL/chap>.

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Appendix A

Eye Tribe and Tobii files

CHAP receives input of a standard data file from Tobii or Eye Tribe. In addition to the standard data files, CHAP requires additional *csv* log files that are created by the user. These *csv* files (see a screenshots in Fig. A1) include data about the trials' onset and offset as well as data about the variables' values and about events' onsets. These log files should have the same name as the main data file with the addition of the suffix - *_events* (for example *sub01_events.csv*) and it should be located in the same folder as the main data file.

a			b		
	timestamp	message		RecordingTimestamp	Event
1		TRIALID 1	2	34402	TRIALID
2	2017-06-25 12:28:08.713	!E TRIAL_EVENT_VAR fixation	3	37402	!E TRIAL_EVENT_VAR word_start
3	2017-06-25 12:28:08.816	!E TRIAL_EVENT_VAR stroop_start	4	41402	!E TRIAL_EVENT_VAR word_stop
4	2017-06-25 12:28:09.899	!E TRIAL_EVENT_VAR response	5	44751	TRIAL_END
5	2017-06-25 12:28:10.575	!E TRIAL_EVENT_VAR response	6	44751	TRIALID
6	2017-06-25 12:28:13.135	!V TRIAL_VAR block practice	7	47751	!E TRIAL_EVENT_VAR word_start
7	2017-06-25 12:28:13.138	!V TRIAL_VAR stimulus_text text_2	8	51751	!E TRIAL_EVENT_VAR word_stop
8	2017-06-25 12:28:13.139	!V TRIAL_VAR stimulus_color color1	9	55083	TRIAL_END
9	2017-06-25 12:28:13.141	!V TRIAL_VAR congruency incongruent	10	55083	TRIALID
10	2017-06-25 12:28:13.143	!V TRIAL_VAR accuracy correct	11	58083	!E TRIAL_EVENT_VAR word_start
11	2017-06-25 12:28:13.144	TRIAL_END	12	62083	!E TRIAL_EVENT_VAR word_stop
12	2017-06-25 12:28:13.145	TRIALID 2	13	65399	TRIAL_END
13	2017-06-25 12:28:13.200	!E TRIAL_EVENT_VAR fixation	14	65399	TRIALID
14	2017-06-25 12:28:14.251	!E TRIAL_EVENT_VAR stroop_start	15	68399	!E TRIAL_EVENT_VAR word_start
15	2017-06-25 12:28:14.710	!E TRIAL_EVENT_VAR response	16	72399	!E TRIAL_EVENT_VAR word_stop
16	2017-06-25 12:28:17.251	!V TRIAL_VAR block practice	17	75732	TRIAL_END
17	2017-06-25 12:28:17.252	!V TRIAL_VAR stimulus_text text_3	18	75732	TRIALID
18	2017-06-25 12:28:17.252	!V TRIAL_VAR stimulus_color color1	19	78732	!E TRIAL_EVENT_VAR word_start
19	2017-06-25 12:28:17.252	!V TRIAL_VAR congruency neutral	20	82732	!E TRIAL_EVENT_VAR word_stop
20	2017-06-25 12:28:17.253	!V TRIAL_VAR accuracy correct	21	86031	TRIAL_END
21	2017-06-25 12:28:17.253	TRIAL_END			

Figure A1. Screenshot of a *csv* file. **(a)** *csv* file for Eye Tribe. This file includes two columns: the log onset (*timestamp*) and the log itself (*message*). **(b)** *csv* file for Tobii. This file includes two columns: the log onset (milliseconds from the begging of the record) (*RecordingTimestamp*) and the log itself (*Event*).

Appendix B

ASL and other device files

For ASL CHAP needs both *asl* and *csv* files. The *asl* file (see a screenshot in Fig. B1a) should be created by using the standard output file of ASL and the *csv* file is an external log file that is created by the user. This *csv* log file (see a screenshot in Fig. B1b) includes data about the trials' onset and offset as well as data about the variables' values and about events' onsets. These log files should have the same name as the main data file with the addition of the suffix - *_events* (for example *sub01_events.csv*) and they should be located in the same folder as the main data file.

CHAP can read input from other eye-trackers, as long as the user adds files with a specific format. The user should provide two files: a *dat* file (csv file that was renamed to this extension; for example *sub01.dat*) and a *csv* file. The *dat* file includes basic information about the pupil (size and gaze position) and the *csv* file includes information about events and variables in the experiment (see a screenshot in Fig. B1c & B1d). These files should have the same name as the main data file with the addition of the suffix - *_events* (for example *sub01_events.csv*) and they should be located in the same folder as the main data file.

a				
	A	B	C	D
1	timestamp	pupil_size	pupil_x	pupil_y
2	1	0	0	0
3	2	0	0	0
4	3	0	0	0
5	4	0	0	0
6	5	0	0	0
7	6	0	0	0
8	7	33.3600006103516	3122	4327
9	8	48.8899993896484	2836	4074
10	9	51.0499992370605	2828	4004
11	10	52.1699981689453	2828	4006
12	11	53.189998626709	2824	3987
13	12	53.629997253418	2826	4009
14	13	52.8199996948242	2827	4006
15	14	54.0200004577637	2823	4010
16	15	53.6399993896484	2825	3997
17	16	54.4799995422363	2824	4009

b	
1	timestamp message
2	1935 TRIALID 1
3	2180 !V TRIAL_EVENT_VAR tone
4	2365 !V TRIAL_EVENT_VAR square
5	2365 !V TRIAL_VAR tone tone_none
6	2365 !V TRIAL_VAR response no
7	2365 TRIAL_END
8	2648 TRIALID 2
9	2833 !V TRIAL_EVENT_VAR tone
10	3018 !V TRIAL_EVENT_VAR square
11	3018 !V TRIAL_VAR tone tone_minus4SL
12	3018 !V TRIAL_VAR response yes
13	3018 TRIAL_END
14	3277 TRIALID 3
15	3403 !V TRIAL_EVENT_VAR tone
16	3588 !V TRIAL_EVENT_VAR square
17	3588 !V TRIAL_VAR tone tone_0SL
18	3588 !V TRIAL_VAR response yes
19	3588 TRIAL_END

c				
1	timestamps	pupil_size	pupil_x	pupil_y
2	2017-06-25 11:15:36.957	16.572	937.6382	537.7338
3	2017-06-25 11:15:36.974	16.8158	938.0964	538.2369
4	2017-06-25 11:15:36.990	16.686	939.4928	539.3295
5	2017-06-25 11:15:37.007	16.97465	940.2045	540.329
6	2017-06-25 11:15:37.024	17.04135	939.5479	542.293
7	2017-06-25 11:15:37.040	16.856	940.7831	544.0555
8	2017-06-25 11:15:37.057	17.0061	941.64	541.7531
9	2017-06-25 11:15:37.074	16.741	943.0785	542.6877
10	2017-06-25 11:15:37.090	16.9848	942.1631	540.8751
11	2017-06-25 11:15:37.107	16.67185	942.5709	542.7808
12	2017-06-25 11:15:37.124	17.5718	941.5947	544.2918
13	2017-06-25 11:15:37.140	17.23105	942.1402	542.7283
14	2017-06-25 11:15:37.157	16.82445	942.7972	543.4584
15	2017-06-25 11:15:37.174	16.4903	943.3441	541.7203
16	2017-06-25 11:15:37.190	16.6602	942.5204	541.2094
17	2017-06-25 11:15:37.207	16.71615	942.1222	542.4844

d	
1	timestamp message
2	2017-06-25 12:28:08.713 TRIALID 1
3	2017-06-25 12:28:08.816 !E TRIAL_EVENT_VAR fixation
4	2017-06-25 12:28:09.899 !E TRIAL_EVENT_VAR stroop_start
5	2017-06-25 12:28:10.575 !E TRIAL_EVENT_VAR response
6	2017-06-25 12:28:13.135 !V TRIAL_VAR block practice
7	2017-06-25 12:28:13.138 !V TRIAL_VAR stimulus_text text_2
8	2017-06-25 12:28:13.139 !V TRIAL_VAR stimulus_color color1
9	2017-06-25 12:28:13.141 !V TRIAL_VAR congruency incongruet
10	2017-06-25 12:28:13.143 !V TRIAL_VAR accuracy correct
11	2017-06-25 12:28:13.144 TRIAL_END
12	2017-06-25 12:28:13.145 TRIALID 2
13	2017-06-25 12:28:13.200 !E TRIAL_EVENT_VAR fixation
14	2017-06-25 12:28:14.251 !E TRIAL_EVENT_VAR stroop_start
15	2017-06-25 12:28:14.710 !E TRIAL_EVENT_VAR response
16	2017-06-25 12:28:17.251 !V TRIAL_VAR block practice
17	2017-06-25 12:28:17.252 !V TRIAL_VAR stimulus_text text_3

Figure B1. (a) *asl* file for the analysis of pupil data from an ASL device. This file includes four columns: the index of the recording sample (*timestamp*), pupil size (*pupil_size*), gaze position on the x-axis (*pupil_x*) and gaze position on the y-axis (*pupil_y*). (b) *csv* file for the analysis of data from an ASL device. This file includes two columns: the index of the recording sample of the log (*timestamp*) and the log itself (*message*). (c) *dat* file for the analysis of data coming from an arbitrary eye-tracker. This file includes four columns: recording timestamps (*timestamp*), pupil size (*pupil_size*), gaze position in both x and y axes (*pupil_x* and *pupil_y*, respectively), (d) *csv* file for the analysis of data from an arbitrary eye-tracker. This file includes two columns: the timestamp of the recording of the log (*timestamp*) and the log itself (*message*) according to CHAP's standards.

Appendix C

CHAP's installation

The installation of CHAP includes three main steps:

1. Downloading CHAP from <https://github.com/ronenno1/chap/archive/master.zip>
 2. Extracting the ZIP file.
 3. Running CHAP_installation.m file (that adds CHAP to the MATLAB path list).
- When working with EyeLink data files:
 - Users who use Windows 32-bit version should go to CHAP's folder and copy manually the *edf2mat/edfapi.dll* file to *C:\Windows\System32*
 - Users who use Windows 64-bit version should go to CHAP's folder and copy manually the *edf2mat/edfapi64.dll* file to *C:\Windows\System32*
 - Users who use Mac should go to CHAP's folder and unzip manually the *edf2mat/edfapi.framework.zip* file and copy *edfapi.framework* to */Library/Frameworks*.

More information about converting EyeLink data files into MATLAB can be found here: <https://github.com/uzh/edf-converter>.

- When working with Eye Tribe data files (txt files given by the default Eye Tribe interface), python should be installed.

Appendix D

External variables and events

CHAP supports the addition of external variables using a *csv* file created by the user (see a screenshot in Fig. D1a). This file should include the variables data for each trial (i.e., trial id, variable name and variable value). Each participant should have a *csv* file with the same name as the main data file with the addition of the suffix - *_vars* (for example *sub01_vars.csv*). This file should be located in the same folder as the main data file. CHAP also supports the addition of external events. By using dedicated *csv* files, the user can specify events that were not logged into the data file during recording (see a screenshot in Fig. D1b).

a			
1	trial_id	congruency	accuracy
2	1	congruent	correct
3	2	incongruent	correct
4	3	congruent	incorrect
5	4	congruent	correct
6	5	congruent	correct
7	6	congruent	incorrect
8	7	congruent	correct
9	8	congruent	correct
10	9	incongruent	correct
11	10	incongruent	incorrect

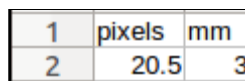
b	
1	event_name
2	fixation
3	stroop_start
4	response

Figure D1. Screenshot of external variables and events files. **(a)** External variables file. This file includes at least two columns (depends on the number of the variables). First, this file must include an index (*trial_id*) of the trial. In addition, for each variable, the file should include a dedicated column (i.e., one variable for the congruency of the trial and another variable for the accuracy of the trial). **(b)** External events file. This file includes one column that includes the event name (*event_name*; e.g., stimuli onset, participant response).

Appendix E

Converting to millimeters

Pupil data can be converted to mm by using a dedicated file (Fig. E1). This file includes data for each participant and should have the same name as the main data file with the addition of the suffix - *_mm* (for example *sub01_mm.csv*). This file should be located in the same folder as the main data file.

A screenshot of a CSV file with two columns. The first column is labeled 'pixels' and the second column is labeled 'mm'. The first row contains the value '1' under 'pixels' and '3' under 'mm'. The second row contains the value '2' under 'pixels' and '20.5' under 'mm'.

1	pixels	mm
2	20.5	3

Figure E1. Screenshot of the *csv* file that is used to convert data from arbitrary units to millimeters. This file includes two columns: one with the mean recorded pupil size given from the eye-tracker (*pixels*) and another one with the actual pupil diameter (*mm*).

Appendix F

Output data

The output data of CHAP includes average pupil size in each bin across trials for each condition (see a screenshot in Fig. F1). This data could be useful for advanced analyses in external code / third party software. CHAP provides information for each trial (see a screenshot in Fig. F2). The data includes information about variables, pupil size and eye-blinks.

1		bin	time(ms)	experiment & congruent & correct	experiment & incongruent & correct
2	20170625a	1	-500	-0.2145	0.26488
3	20170625a	2	-483	-0.34954	0.062003
4	20170625a	3	-466	-0.15081	-0.058539
5	20170625a	4	-449	-0.76248	-0.13715
6	20170625a	5	-432	-0.83687	-0.2468
7	20170625a	6	-414	-0.73851	-0.443
8	20170625a	7	-397	-0.82765	-0.42534
9	20170625a	8	-380	-0.052351	-0.25643
10	20170625a	9	-363	-0.084895	-0.6272
11	20170625a	10	-346	-0.72981	-0.30029
12	20170625a	11	-329	-0.8371	-0.2895
13	20170625a	12	-312	-0.90831	-0.31285
14	20170625a	13	-295	-0.91142	-0.43762
15	20170625a	14	-278	-0.96953	-0.36889
16	20170625a	15	-260	-0.83827	-0.29859
17	20170625a	16	-243	-0.94076	-0.33351
18	20170625a	17	-226	-0.82743	-0.31978
19	20170625a	18	-209	-0.95933	-0.2533
20	20170625a	19	-192	-0.74894	-0.2305
21	20170625a	20	-175	-0.41839	-0.15417

Figure F1. Screenshot of an output data file (*time-course_data.csv*). This file includes information about each bin in the selected time-window for each selected condition.

	A	B	C	D	E	F	G	H	I	J
1	participant_id	trial_id	block	stimulus_text	stimulus_color	congruency	accuracy	event_fixation	event_stroop_start	event_response
2	20170625a	11	experiment	text_3	color1	neutral	correct	67	1117	1937
3	20170625a	12	experiment	text_2	color2	congruet	correct	55	1088	1411
4	20170625a	13	experiment	text_3	color1	neutral	correct	59	1110	2409
5	20170625a	14	experiment	text_2	color2	congruet	correct	47	1081	1399
6	20170625a	16	experiment	text_2	color1	incongruet	correct	57	1090	2010
7	20170625a	17	experiment	text_2	color1	incongruet	correct	45	1095	1506
8	20170625a	18	experiment	text_1	color2	incongruet	correct	33	1085	1445
9	20170625a	19	experiment	text_2	color2	congruet	correct	52	1086	1504
10	20170625a	20	experiment	text_1	color1	congruet	correct	40	1074	1547
11	20170625a	21	experiment	text_2	color1	incongruet	correct	45	1080	1454
12	20170625a	22	experiment	text_1	color2	incongruet	correct	48	1082	1457

K	L	M	N	O	P	Q	R	S
event_trial_end	event_trial_start	trial_mean	trial_max	trial_min	first_bin	last_bin	valid_blinks	blinks_mean
3450		0 7.994659199209	18.30059885	-10.5556456514	-10.55564565137	9.5458992641647	0	NaN
2917		0 0.597811682483	6.235655911	-8.43225037845	-3.589587093573	-8.432250378446	0	NaN
3917		0 NaN	NaN	NaN	NaN	NaN	0	NaN
2917		0 4.062863255849	14.12766335	-7.10152318028	-7.101523180276	2.4214021240272	0	NaN
3517		0 0.570934309865	8.875304945	-11.6389571137	-3.584102179186	-9.961797371938	0	NaN
3017		0 3.202647659852	10.89865445	-7.91210993415	-7.912109934154	3.8511308330948	0	NaN
2950		0 0.163553101322	5.597445246	-4.11833240892	-2.068339849299	-2.093704765899	0	NaN
3017		0 1.418353120341	6.645892681	-2.53126496696	-0.827988310474	-2.531264966955	0	NaN
3050		0 4.489508146349	9.932360574	-3.86775662829	-2.409470449803	-1.269072519759	0	NaN
2967		0 -3.78415435581	2.204293583	-18.2294533593	-3.761269451649	-18.22945335927	1	183.33333333
2967		0 6.069155080217	15.0904697	-10.758026592	-9.660185068164	6.151831016355	0	NaN

Figure F2. Screenshot of an output data file (*trials_data.csv*). This file has information for each trial including events onset and descriptive statistics.

Appendix G

Group analysis

When running group analysis, CHAP creates a *csv* files that includes information about number of valid trials and number of excluded trials for each condition for each participants (Fig. G1a). In addition, CHAP provides a *csv* files that includes information about the mean events' onset for each trial for each participant (Fig. G1b).

a

1	participant_id	experiment & congruent & correct	experiment & incongruent & correct
2	20170625a	112	112
3	20170625b	115	115
4	20170625c	120	118
5	20170625d	108	105
6	20170703a	47	46
7	20170703b	115	110
8	20170703c	53	43
9	20170703d	86	80
10	20170705a	81	79
11	20170705b	104	105

b

1	participant_id	condition	outliers	good_trials	stroop_start	response	trial_end
2	20170625a	experiment & congruent & correct	3	112	0	476	1983
3	20170625a	experiment & incongruent & correct	3	112	0	502	2010
4	20170625b	experiment & congruent & correct	4	115	0	550	2059
5	20170625b	experiment & incongruent & correct	3	115	0	569	2078
6	20170625c	experiment & congruent & correct	0	120	0	523	2032
7	20170625c	experiment & incongruent & correct	1	118	0	534	2043
8	20170625d	experiment & congruent & correct	7	108	0	438	1943
9	20170625d	experiment & incongruent & correct	12	105	0	472	1976
10	20170703b	experiment & congruent & correct	4	115	0	432	1937
11	20170703b	experiment & incongruent & correct	5	110	0	469	1975

Figure G1. Screenshot of output data files. **(a)** Number of valid trials and number of trials that were excluded from analysis, for each condition for each participant. **(b)** Information about the mean events' onset for each trial for each participant.