



# 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. Although several eyetracker systems on the market can 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 graphical user interface for processing and analyzing pupillometry data. Our software creates uniform conventions for the preprocessing and analysis of pupillometry data and provides a quick and easy-to-use 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, 2014a).

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 eyetracking devices (e.g., EyeLink, Tobii, Ergoneers, and Mangold), which provide information on eye movements as well as pupil size. Although there are open-source tools for processing the eye movement data recorded by these devices (Li, 2017; Sogo, 2013; Zhegadlo & Marmalyuk, 2015), there is a lack of tools for processing and analyzing pupillometry data.

Some of the current eyetracker companies offer basic tools for processing pupillometry data (e.g., Data Viewer by SR

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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. Although there have been some attempts to provide guidelines and scripts for the preprocessing 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 graphical user interface (GUI) for processing and analyzing pupillometry data. The software receives input of a standard data file from common eyetrackers such as EyeLink (.edf file), Tobii, Applied Science Laboratories (ASL), or Eye Tribe (.csv file), and provides both preprocessing and analysis of the data. Our software aims to create uniform conventions for the preprocessing and analysis of pupillometry data, and to offer a quick and easy-to-implement tool for researchers interested in pupillometry.

## CHAP's input

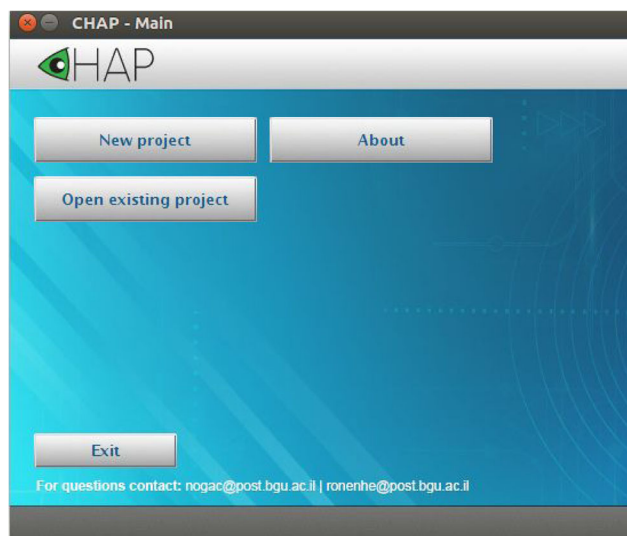
CHAP receives input of a standard data file from various eyetrackers. It receives input from EyeLink (.edf file), Eye Tribe (both .txt and .csv files; see Appendix A for an example), and Tobii and ASL eyetrackers (.csv files; see Appendixes A and B for examples). CHAP also supports data files from other eyetracker 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 eyetracker and on specific task requirements. For processing EyeLink data files (.edf), CHAP uses the EDFMEX software (Beta Version 0.9; SR Research, Ontario, Canada) and the EDFMAT software (Version 1.6; developed by Adrian Etter and Marc Biedermann, University of Zurich), which 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 the files created by PyGaze (Dalmajjer, Mathôt, & Van der Stigchel, 2014) or PsychoPy (Peirce, 2007), can be converted to both .dat and .csv files (see Appendix B). For processing input files in both a .dat and a .csv format, CHAP does not require any additional packages.

## Running CHAP

After installing CHAP (see Appendix C for the installation instructions), the user should type *chap* in MATLAB's command window 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 in the main GUI (see Fig. 1). Next the user will be asked to choose a data file, as follows: 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).

## 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 the *x*- and *y*-positions of the pupil) and removes irrelevant information saved by the eyetracking 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 in the main GUI (Fig. 1). This compression of the data, which results in a .chp file that is approximately ten times smaller than the original data file, allows for fast and efficient processing of the data.



**Fig. 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 open an existing (already preprocessed) data file (by clicking on *Open existing project*).

## Trials, variables, and events

Pupil size is usually recorded in experiments that consist of different trial types. CHAP uses user-defined information 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).

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 the 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 in which 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 experiment 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 in which 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 (which is used in EyeLink): *[milliseconds before the trial's ending] [event name]*. This 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 preprocessing

After CHAP reads the data and converts it to a .chp file, pupil data (pupil size in pixels or any other units) is preprocessed. Preprocessing includes:

1. *Exclusion of outlier samples* (Akdoğan, Balcı, & 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 Pre-processing* GUI (see Fig. 2), will be converted to missing (not a number: NaN) values.
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 interpolation<sup>1</sup> (Mathôt, 2013; Mathôt et al., 2018; Smallwood et al., 2011; Wainstein et al., 2017). The user can select the interpolation method from a dropdown list that appears in the *Data Pre-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), which 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 Pre-processing* GUI (see Fig. 2). Accurate correction of blinks is highly important, because 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, 2019; Nyström, Andersson, Holmqvist, & van de

<sup>1</sup> 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).

Weijer, 2013; Schmidtke, 2014; Wainstein et al., 2017). CHAP removes trials on the basis of a user-defined percentage of missing pupil observations within a trial (*Missing values (%)* text field in the *Data Pre-processing* GUI; see Fig. 2). Missing observations occur during blinks, head movements, or inability of the eyetracking 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 Pre-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 ten valid congruent trials), an error message will appear and the participant will not be included in the analysis.

## Selecting variables and events

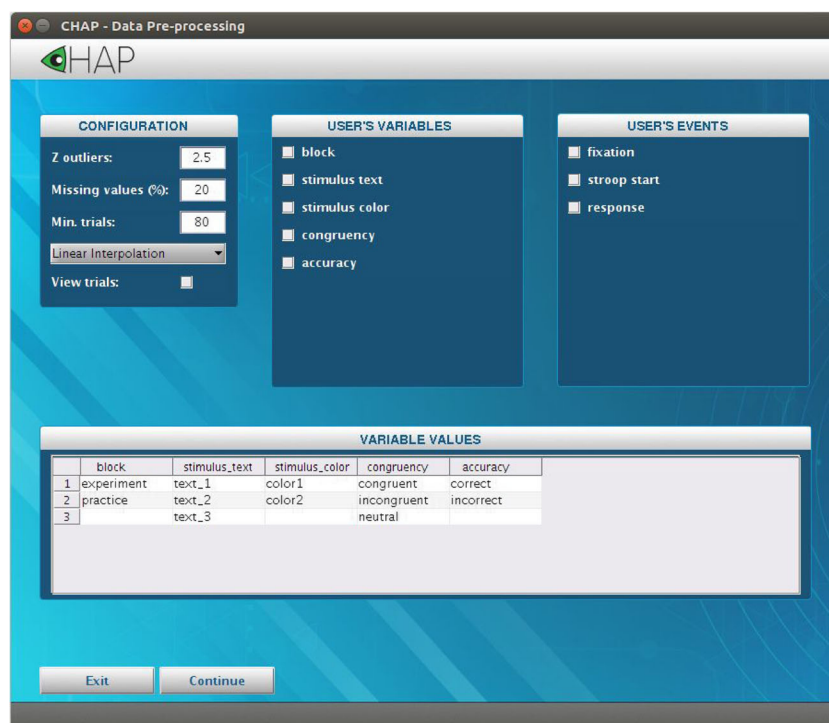
The *Data Pre-processing* GUI presents lists of the variables and events that were logged during the experiment (see Fig. 2). The user can choose what variables and events he or she wants to analyze. After selecting the parameters

for excluding trials and participants and the desired variables and events, the user should click the *Continue* button (see the screenshot in Fig. 2). Then, the *Condition-selecting* GUI will be opened. This GUI allows the user to select the desired conditions (up to seven) from a list. The list includes all the possible combinations, depending on the selected variables (see the example in Fig. 3).

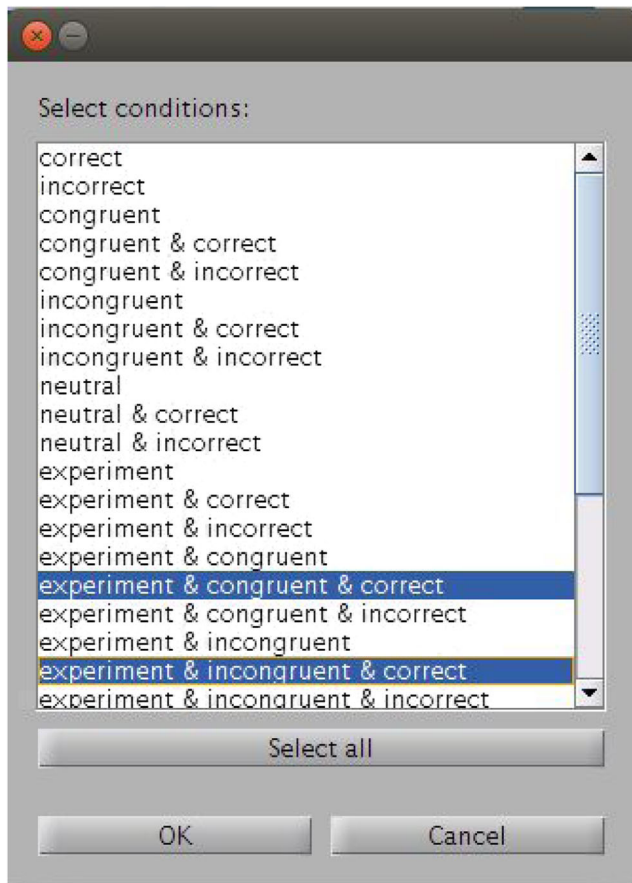
## Time-course visualization

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.



**Fig. 2** Screenshot of the GUI for data preprocessing. 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).



**Fig. 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.

### Advanced processing options

In addition to basic preprocessing of the data (Fig. 5a), CHAP supports several advanced analysis features (Fig. 5b–g). These features can be selected by the user from the *Advanced Processing Options and Time-Course Visualization* GUI (see the 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 into chunks that include samples with a 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 the case of comparing data collected using different eyetrackers or different sampling rates (Titz, Scholz, & Sedlmeier, 2018), or to correlate between pupil size and another measure, such as

blood-oxygen-level dependent (BOLD) activity (Murphy, O’Connell, O’Sullivan, Robertson, & Balsters, 2014b; Yellin, Berkovich-Ohana, & Malach, 2015).

**Time window** In most psychological experiments, each trial includes several events (e.g., fixation cross, target, intertrial 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 are 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 s in some trials, and after 2.5 s in other trials). This can happen when stimulus onset is determined by the participant response time (which varies from trial to trial) or when a stimulus appears after a variable inter-stimulus interval (ISI).

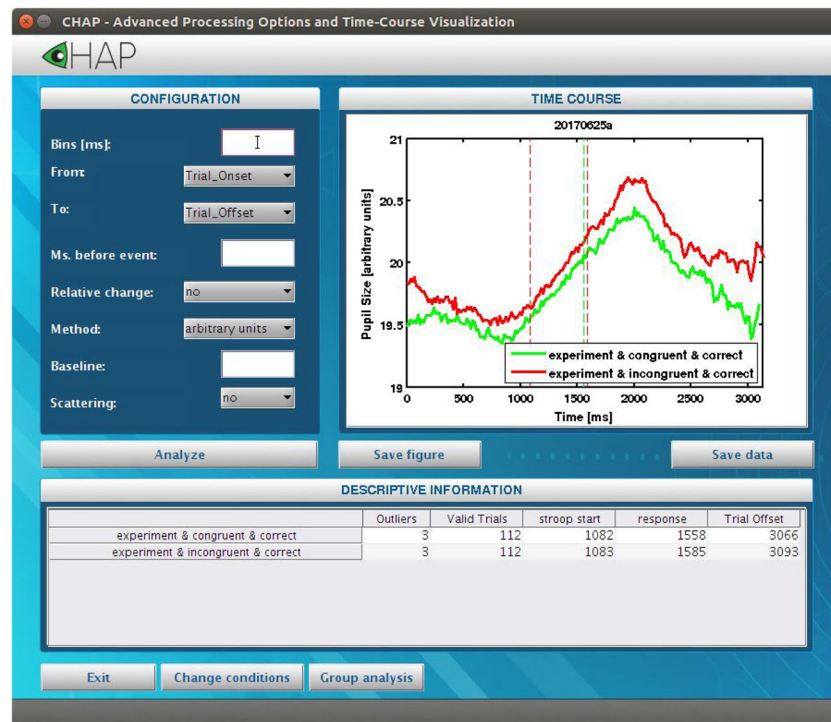
**Relative change** Instead of using the units recorded by the eyetracker device (e.g., number of pixels, in the case of an EyeLink device), the user can convert the data to a relative change score (Mathôt et al., 2018). The relative change indicates either the difference from baseline (i.e., subtractive 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): (Fig. 5f).

$$relative\% = 100 \cdot \frac{value}{baseline}$$

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

**Conversion to Z-scores/millimeters** Most eyetrackers provide pupil data in arbitrary units. These units (or values) are dependent on the eyetracker definitions during recording, the position of the camera, and 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 were 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 on the basis of the entire time course of the participant (i.e., the mean and *SD* will be calculated on all valid trials for that



**Fig. 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.

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-unit sizes. Pupil size is recorded in either diameter or area measurement, and CHAP recognizes the right measurement after the data are loaded.

CHAP uses the following equations to get the size 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,

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

where  $pupil_{diameter}[arbitrary\_units]$  is described by

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

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

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

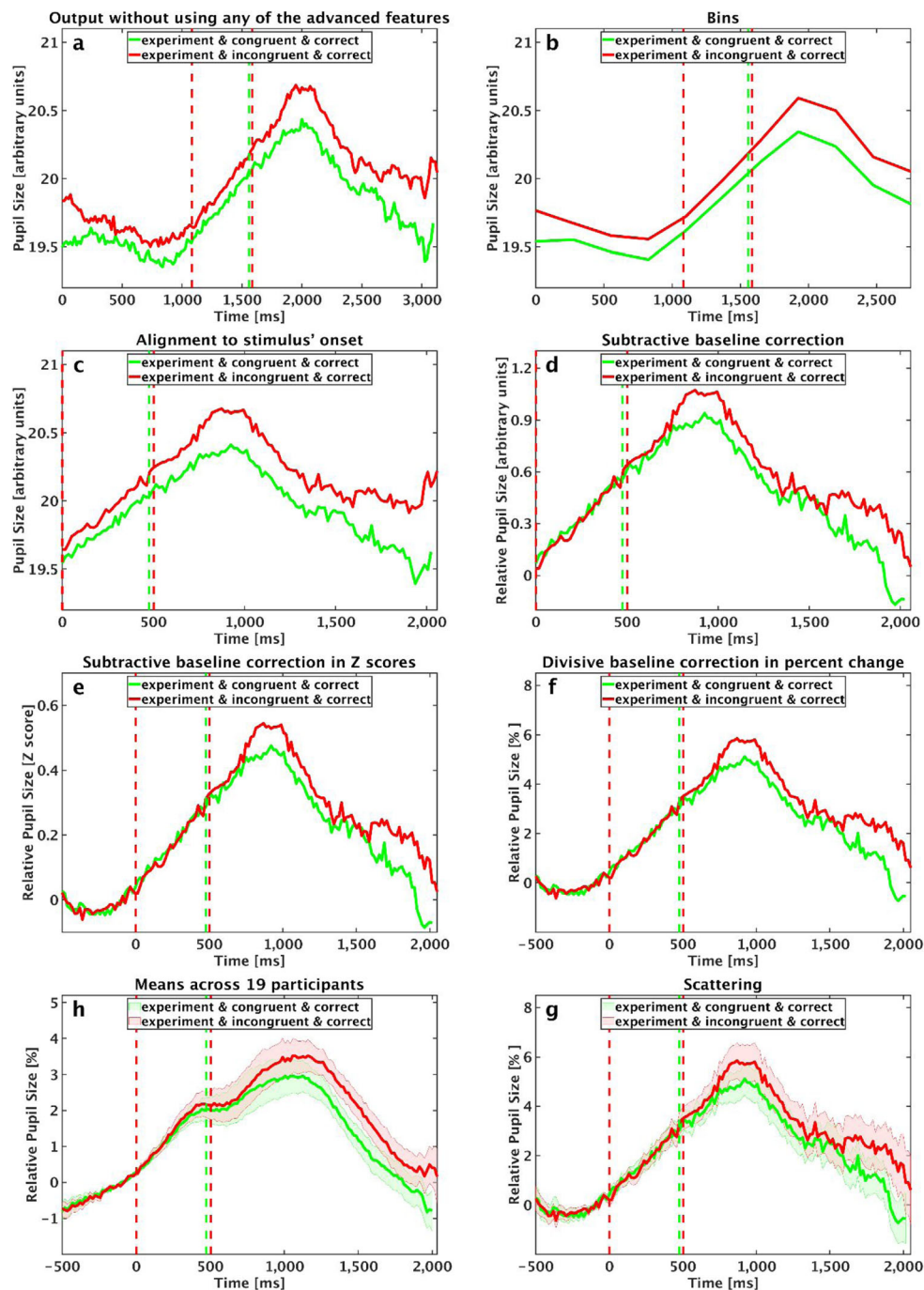
For conversion of the data to millimeters, the user should add a .csv file for each participant, with the same name as the main data file and the addition of the suffix *\_mm* (e.g., sub01\_mm.csv). This file should be located in the same folder as the main data file (see Appendix E).

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

### Output files

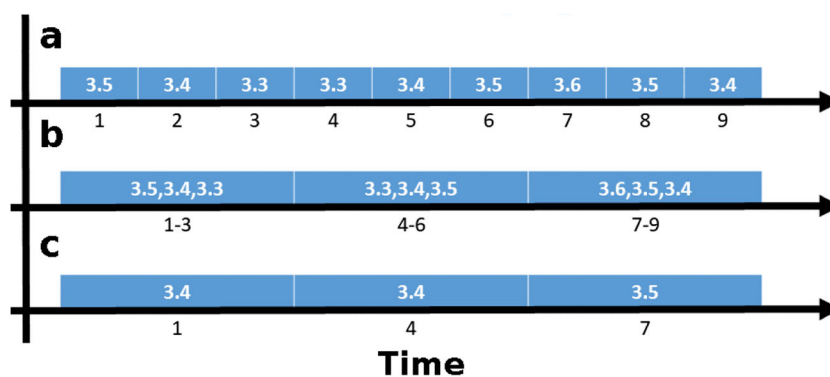
CHAP saves four types of output files. The presented figure can be saved by the user as a .png (standard image file) or as a .fig (standard MATLAB figure file) by clicking the *Save data* button in the *Advanced Processing Options and Time-Course Visualization* GUI (Fig. 4). In addition, the processed data can be saved as a .csv or a MATLAB file that contains all the data concerning the relevant variables and events for each participant (by clicking the *Save data* button in 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). These data could be used later for analysis by external code/third-party



**Fig. 5** Examples of CHAP's features: Mean pupil size as a function of time in a two-color Stroop task run on 19 participants (Exp. 1 in Hershman & Henik, 2019). 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, red). 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. Panels a–g present data for one participant, whereas panel 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 (since 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 times. (d) Aligned data in relative change (subtractive baseline correction, in pixels). (e) Aligned data in normalized relative change (subtractive baseline correction). The data are normalized by using z scores. (f) Normalized relative changes (divisive baseline correction, as a percentage) from 500 ms before Stroop stimulus onset until trial offset. (g) Normalized relative change (divisive baseline correction, as a percentage) from 500 ms before stimulus onset until trial offset. Here the shades around the curves represent one standard error from the mean. (h) Group analysis across 19 participants: Normalized relative change (divisive baseline correction, as a percentage) from 500 ms before stimulus onset until trial offset. The shades around the curves represent one standard error from the mean. For all figures with a baseline correction, the baseline was the average for 200 ms before Stroop stimulus onset.



**Fig. 6** Schematic example of down-sampling using bins. In this examples, the sampling rate is 1,000 Hz (1 sample every 1 ms), and each bin is 3 ms (three samples, in this case). (a) Pupil data in millimeters for each

sample. (b) Chunks of three samples (corresponds to 3-ms bins). (c) Average pupil size for each bin.

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, and 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 the mean pupil size in the first and last bins and the minimum and maximum pupil size values 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](#)), measures 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 means 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 (*time-course\_data.csv* and *trials\_data.csv*; see [Appendixes F & G](#)).

## Parameters for statistical analysis

CHAP provides commonly used parameters for analysis, such as the mean ([Binda et al., 2014](#); [de Gee, Knapen, & Donner,](#)

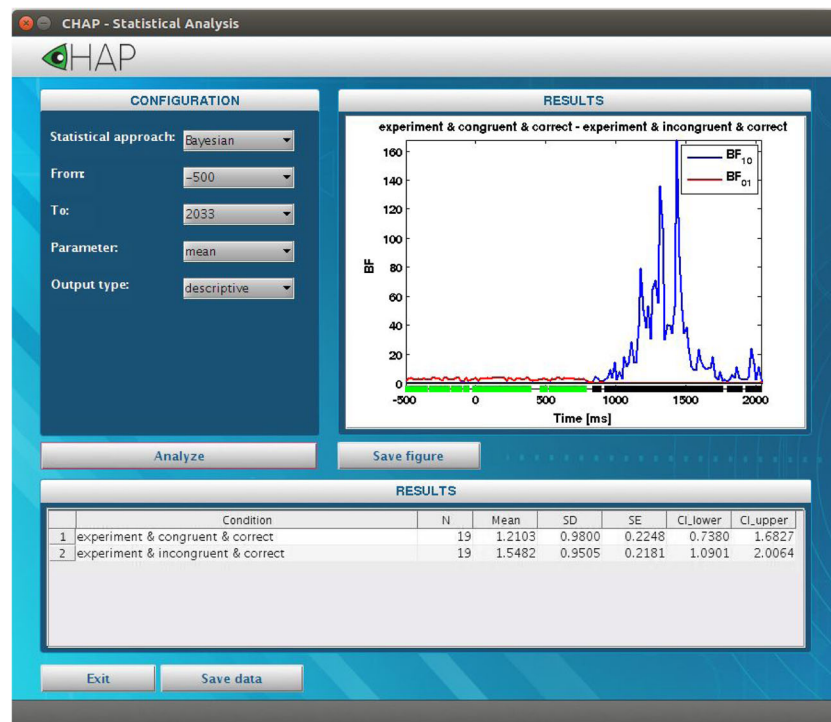
[2014](#); [Hemmati, 2017](#); [Laeng, Ørbo, Holmlund, & Miozzo, 2011](#)), peak amplitude ([Binda & Murray, 2015](#); [Hemmati, 2017](#); [Hess & Polt, 1964](#); [Schmidtke, 2014](#)), peak latency ([Hess & Polt, 1964](#); [Koelewijn, de Kluiver, Shinn-Cunningham, Zekveld, & Kramer, 2015](#); [Laeng 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* fields in the *Statistical Analysis* GUI; [Fig. 7](#)), these parameters will be calculated on the basis of the data within the selected time window (see the table in [Fig. 7](#)).

## Statistical analysis

CHAP provides two approaches to statistical analysis. CHAP has the option to run a repeated measures analysis of variance (ANOVA). The output of this analysis includes the *F* value (including the degrees of freedom), *p* value,  $\eta_p^2$ , and *MSE*. 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 a Cauchy prior width of  $r = .707$  for effect size based 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 over the null hypothesis. Similar to the output of the parametric analysis, by selecting the Bayesian approach (*Statistical approach* dropdown in the *Statistical Analysis* GUI; [Fig. 7](#)), CHAP will run and present the output for the Bayesian





**Fig. 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 a 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 for no differences between conditions. The Bayes factor threshold value that CHAP uses (hard-coded) for this analysis is 3 (Jeffreys, 1961). In the present example, there is a meaningful similarity between conditions from  $-500$  ms to  $750$  ms, and a meaningful difference between conditions from  $1,000$  to  $2,000$  ms.

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 in a selected time window.

Similar to the analysis described above, CHAP supports both Bayesian and classical approaches (selected from the *Statistical approach* dropdown in 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 either a Holm–Bonferroni-corrected  $p$  value as a function of time (by using the classical approach) or Bayes factors (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 (using the Bayesian approach), CHAP also provides inference information about the differences and similarities between conditions.

## Discussion

In this article, we have 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 preprocessing and analysis of pupillometry data. CHAP supports data coming from a wide range of eyetracker 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 preprocessing, analysis, and visualization of the data. Besides that, by introducing CHAP we suggest uniform conventions for the preprocessing 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

operating systems (see [Appendix C](#) for instructions), and experienced users can also modify the code if they wish (since the MATLAB script is available after installation).

Several challenges in the analysis of pupil data should be addressed in future work. First, because pupil size is influenced by gaze position (Brisson et al., 2013; Gagl, Hawelka, & Hutzler, 2011), these 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 incorporated in future CHAP versions. Second, currently CHAP supports only 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-group 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 article has 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 the screenshots in Fig. 8) 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* (e.g., sub01\_events.csv), and it should be located in the same folder as the main data file.

## Appendix B: ASL and other device files

For ASL, CHAP needs both *.asl* and *.csv* files. The *.asl* file (see the screenshot in Fig. 9a) 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 the screenshot in Fig. 9b) 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* (e.g., sub01\_events.csv) and they should be located in the same folder as the main data file.

CHAP can read input from other eyetrackers, 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; e.g., 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. 9c and B1d). These files should have the same name as the main data file with the addition of the suffix *\_events* (e.g., sub01\_events.csv), and they should be located in the same folder as the main data file.

## 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.

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

**Fig. 8** Screenshot of a .csv file. (a) The .csv file for Eye Tribe. This file includes two columns: the log onset (timestamp) and the log itself (message). (b) The .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).

a					b			
1	timestamp	A	B	C	D	1	timestamp	message
2	1	pupil_size	pupil_x	pupil_y		2	1935	TRIALID 1
3	2		0	0	0	3	2180	!V TRIAL_EVENT_VAR tone
4	3		0	0	0	4	2365	!V TRIAL_EVENT_VAR square
5	4		0	0	0	5	2365	!V TRIAL_VAR tone tone_none
6	5		0	0	0	6	2365	!V TRIAL_VAR response no
7	6		0	0	0	7	2365	TRIAL_END
8	7	33.3600006103516	3122	4327		8	2648	TRIALID 2
9	8	48.8899993896484	2836	4074		9	2833	!V TRIAL_EVENT_VAR tone
10	9	51.0499992370605	2828	4004		10	3018	!V TRIAL_EVENT_VAR square
11	10	52.1699981689453	2828	4006		11	3018	!V TRIAL_VAR tone tone_minus4SL
12	11	53.189998626709	2824	3987		12	3018	!V TRIAL_VAR response yes
13	12	53.629997253418	2826	4009		13	3018	TRIAL_END
14	13	52.819996948242	2827	4006		14	3277	TRIALID 3
15	14	54.0200004577637	2823	4010		15	3403	!V TRIAL_EVENT_VAR tone
16	15	53.6399993896484	2825	3997		16	3588	!V TRIAL_EVENT_VAR square
17	16	54.4799995422363	2824	4009		17	3588	!V TRIAL_VAR tone tone_OSL
						18	3588	!V TRIAL_VAR response yes
						19	3588	TRIAL_END

c					d		
1	timestamps	pupil_size	pupil_x	pupil_y	1	timestamp	message
2	2017-06-25 11:15:36.957	16.572	937.6382	537.7338	2	2017-06-25 12:28:08.713	TRIALID 1
3	2017-06-25 11:15:36.974	16.8158	938.0964	538.2369	3	2017-06-25 12:28:08.816	!E TRIAL_EVENT_VAR fixation
4	2017-06-25 11:15:36.990	16.686	939.4928	539.3295	4	2017-06-25 12:28:09.899	!E TRIAL_EVENT_VAR stroop_start
5	2017-06-25 11:15:37.007	16.97465	940.2045	540.329	5	2017-06-25 12:28:10.575	!E TRIAL_EVENT_VAR response
6	2017-06-25 11:15:37.024	17.04135	939.5479	542.293	6	2017-06-25 12:28:13.135	!V TRIAL_VAR block practice
7	2017-06-25 11:15:37.040	16.856	940.7831	544.0555	7	2017-06-25 12:28:13.138	!V TRIAL_VAR stimulus_text text_2
8	2017-06-25 11:15:37.057	17.0061	941.64	541.7531	8	2017-06-25 12:28:13.139	!V TRIAL_VAR stimulus_color color1
9	2017-06-25 11:15:37.074	16.741	943.0785	542.6877	9	2017-06-25 12:28:13.141	!V TRIAL_VAR congruency incongruet
10	2017-06-25 11:15:37.090	16.9848	942.1631	540.8751	10	2017-06-25 12:28:13.143	!V TRIAL_VAR accuracy correct
11	2017-06-25 11:15:37.107	16.67185	942.5709	542.7808	11	2017-06-25 12:28:13.144	TRIAL_END
12	2017-06-25 11:15:37.124	17.5718	941.5947	544.2918	12	2017-06-25 12:28:13.145	TRIALID 2
13	2017-06-25 11:15:37.140	17.23105	942.1402	542.7283	13	2017-06-25 12:28:13.200	!E TRIAL_EVENT_VAR fixation
14	2017-06-25 11:15:37.157	16.82445	942.7972	543.4584	14	2017-06-25 12:28:14.251	!E TRIAL_EVENT_VAR stroop_start
15	2017-06-25 11:15:37.174	16.4903	943.3441	541.7203	15	2017-06-25 12:28:14.710	!E TRIAL_EVENT_VAR response
16	2017-06-25 11:15:37.190	16.6602	942.5204	541.2094	16	2017-06-25 12:28:17.251	!V TRIAL_VAR block practice
17	2017-06-25 11:15:37.207	16.71615	942.1222	542.4844	17	2017-06-25 12:28:17.252	!V TRIAL_VAR stimulus_text text_3

**Fig. 9** (a) The .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) The .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) The .dat file for the analysis of data coming from an

arbitrary eyetracker. 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) The .csv file for the analysis of data from an arbitrary eyetracker. This file includes two columns: the timestamp of the recording of the log (timestamp) and the log itself (message) according to CHAP's standards.

a				b	
1	trial_id			1	event_name
2		1	congruent	2	fixation
3		2	incongruent	3	stroop_start
4		3	congruent	4	response
5		4	congruent		
6		5	congruent		
7		6	congruent		
8		7	congruent		
9		8	congruent		
10		9	incongruent		
11		10	incongruent		

**Fig. 10** 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 D: External variables and events

CHAP supports the addition of external variables using a .csv file created by the user (see the screenshot in Fig. 10a). 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* (e.g., sub01\_vars.csv). This file should be located in the same folder as the main data file.

1	pixels	mm
2	20.5	3

**Fig. 11** 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 eyetracker (pixels), and another one with the actual pupil diameter (mm)

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 the screenshot in Fig. 10b).

## Appendix E: Converting to millimeters

Pupil data can be converted to millimeters by using a dedicated file (Fig. 11). 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* (e.g., sub01\_mm.csv). This file should be located in the same folder as the main data file.

## Appendix F: Output data

The output data from CHAP include average pupil size in each bin across trials for each condition (see the screenshot in Fig. 12). These data could be useful for advanced analyses using external code/third-party software. CHAP provides information for each trial (see the screenshot in Fig. 13). The data

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

**Fig. 12** 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

Fig. 13 Screenshot of an output data file (trials\_data.csv). This file has information for each trial including events onset and descriptive statistics.

include information about variables, events, pupil size, and eye blinks.

of excluded trials for each condition for each participants (Fig. 14a). In addition, CHAP provides a .csv files that includes information about the mean events' onset for each trial for each participant (Fig. 14b).

## Appendix G: Group analysis

When running a group analysis, CHAP creates a .csv files that includes information about number of valid trials and number

**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

Fig. 14 Screenshot of output data files. (a) Number of valid trials for each condition for each participant. (b) Information about the mean events' onset for each trial for each participant.

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