Pupil size reflects covert attention unconsciously biased toward regularities

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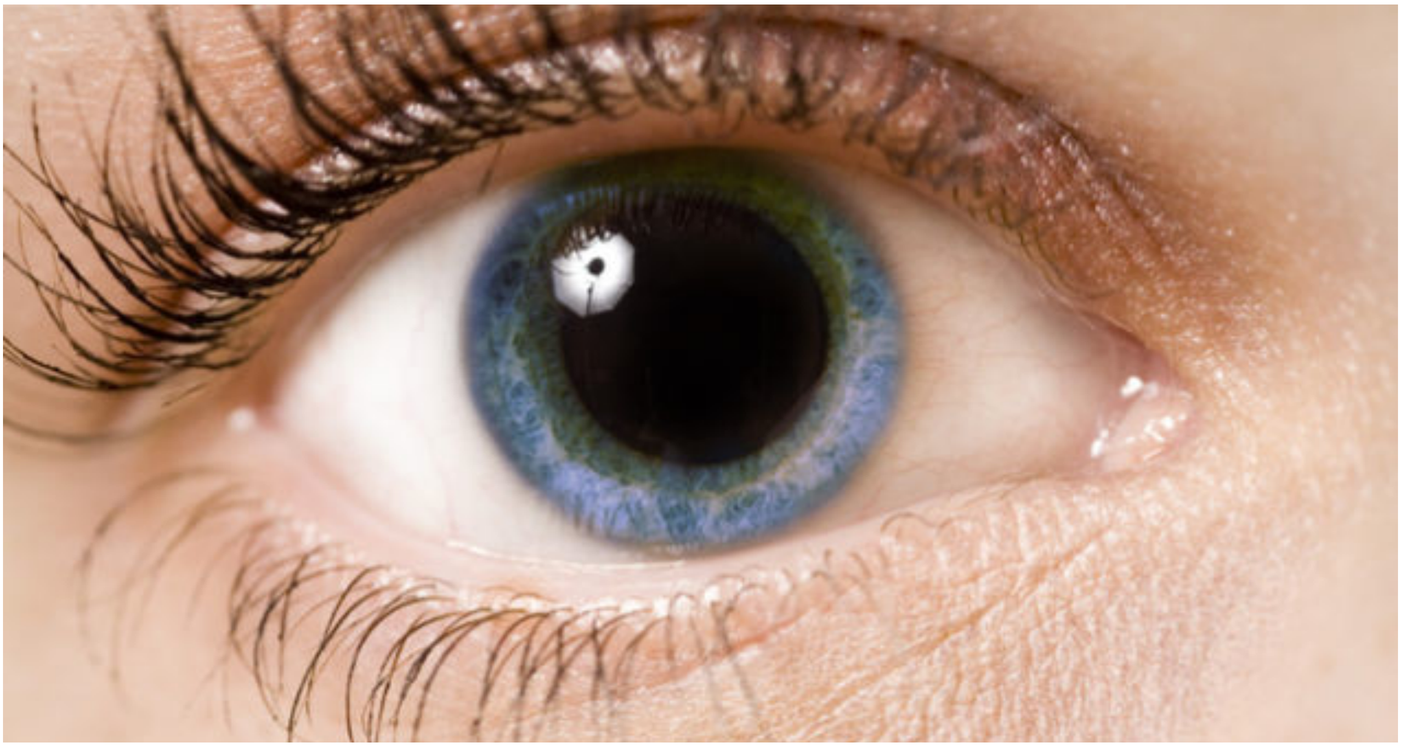

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Abstract

The brain uses statistical learning to extract information from regularities in the environment. To facilitate this process, attention is unconsciously biased towards the regularities. To investigate how attention is biased and how this learning process progresses, we monitored covert attention by using the pupillary light response. We predicted that behavioural data would show statistical learning occurred. In addition, we hypothesised that pupil size reflects unconscious attention biased toward regularities and indicates the onset and speed of the learning process over time. We conducted an experiment using sources containing temporal regularities and noisier sources of different luminance. Thereby, we biased covert attention and measured reaction time and pupil size data. We did find promising data on these hypotheses, but did not find significant results. We speculate that a shortage of usable trials and a conscious awareness of the regularities by the participants led to these results.

Introduction

Our perception of the visual world is facilitated by attention. Attention can either be drawn exogenously or directed endogenously. These mechanisms are driven by salient sources or internally represented goals, respectively (Corbetta and Schulman, 2002; Posner, 1980). Zhao and colleagues recently stated that attention is biased in a third way, not distinctively accounted for by salience or intention (Zhao et al., 2013). The recently proposed type of controlling attention is described by the widely researched phenomena called statistical learning. This type of learning explains how the brain extracts regularities from the environment that appear over space and time. Statistical learning has many similarities with implicit learning, as it both occurs without conscious intend. Some researchers state that it originates from the same mechanism, (Perruchet and Pacton, 2006; Turk-Brown et al., 2005, 2009), but this is an ongoing debate. The term statistical learning was first proposed by Saffran and colleagues when researching the learning processes of infants (Saffran, Aslin and Newport, 1996). Statistical learning occurs automatically, without the intention to learn (Fiser and Aslin, 2001; Turk-Brown et al., 2005), incidentally (Fiser and Aslin, 2002) and is sensitive to information distributed over time (Turk-Brown et al., 2009). Therefore, no internal goals are needed for statistical learning. Additionally, regularities are not detected by salience, but by interaction with internal representations of prior stimuli (Zhao et al., 2013). To summarise, the brain extracts regularities from the environment through statistical learning. Attention is biased unconsciously, neither by internal goals nor salience.

By recording regularities, the brain improves, e.g., learning of object labels (Graf Estes et al., 2007), object categorisation (Turk-Brown et al., 2010) and visual short-term memory capacity (Bradi, Konkle and Alvarez, 2009; Umemoto et al., 2010). Although this expounds the usefulness of statistical learning, most research only reports explicit knowledge acquired (e.g., conscious preference of regularities). Furthermore, implicit knowledge is required to understand the phenomena and the underlying mechanisms (Batterink et al., 2015). Until now, existing evidence about implicit knowledge was derived from reaction time data and brain monitoring. For example, Zhao and colleagues found that, during an exposure phase, temporal regularities in one spatial location attract unconscious attention compared to noisy sources in other spatial locations. In the search task following, the location biased by statistical learning showed enhanced reaction time. In fact, the participants overtly attended the location more than the noisier locations, although the regularities did not provide information for better performance on the search task (Zhao et al., 2013). The overt shifts of attention and reaction time data indicate a covert attentional bias towards the regularities, reflecting the implicit effects of statistical learning. In addition, Turk-Brown found that statistical learning already occurs after 3-4 exposure trials (Turk-Brown et al., 2009). However, habituation effects in the second half (after 40 trials) have been reported (Zhao et al., 2013). To support the known implicit effects of statistical learning and explore the mechanisms, covert attention must therefore be researched over the duration of an experiment.

Covert attention is hard to track. It is mostly an assumption from behavioural data or derived from brain potentials (Regan, 1989; Morgan et al., 1996; Müller et al., 2003; Störmer et al., 2013). However, the pupil also responds to covert attention shifts. In the past, it was believed that the pupil only responses to direct light in a reflexive way. Recent research found that the pupillary light response is not entirely reflexive and that pupil size is influenced by covertly attending a bright or dark stimulus (Binda, Pereverzeva, & Murray, 2013; Mathôt et al., 2013, 2014; Naber, Alvarez, & Nakayama, 2013). The same effect has been recorded when covert attention is biased exogenously (Mathôt et al., 2014). The process could be explained by understanding the purpose. The pupil is trying to facilitate a better input from outside the focus, where the brain focuses its attention. This means that the pupillary light response is the first step in the perception of a stimulus. The process starts as soon as light enters the eye and after evaluation directs covert attention to the location (Mathôt et al., 2013). By recording the pupil size, it is possible to measure covert attention, provided there is a difference in luminance of the supposed stimuli. Therefore, we hypothesised that pupil size reflects an exogenous covert attention bias.

To ensure the same behavioural effect of statistical learning, we used the experimental design of Zhao and colleagues with an addition of bright and dark stimuli to measure pupil response. To confirm statistical learning occurred it was necessary that the pupil data was accompanied by reaction time and accuracy data. The experiment we conducted used temporally structured sources to bias unconscious covert attention to spatial locations. We predicted reaction times to be lower and accuracy to be higher on the structured locations. Moreover, we hypothesised that the mean pupil size would be higher when regularities appear in dark stimuli relative to bright stimuli. Furthermore, this effect was expected to have a fast onset and slow decline over time.

This research is relevant for the discipline artificial intelligence for two reasons. First, the process of human learning is further investigated. Especially statistical learning is researched, providing new evidence for the debate on the difference between statistical and implicit learning. In this way, we enhance the knowledge on the processes of learning, which enhances the literature on the human brain. Further elaborating the pupillary light response provides the field with a more complete picture of human perception. Second, the goal of the discipline is to program an artificial intelligent system, which needs a comprehensive image of learning processes of the human mind. By providing more knowledge about human perception, this research enables perfecting the ideas for, e.g., new eye tracking software or game development. For example, finding out how the pupils react to covert attention, could help to develop new software that not only tracks where the eye is looking at, but what the person exactly perceives.

Methods

Participants, apparatus and software

Twenty-five observers (fifteen female, ten male; average age: 23,4) participated in the experiment; all provided informed consent. An Eyelink 1000 (SR Research, Mississauga, ON, Canada) with a sampling rate of 1000 Hertz was used to record the left eye. The LG IPS LED stimuli monitor (1280 x

800 px, 60 Hz) was stationed 70 cm from the observer. The experiment was presented with MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Stimuli and Procedure

Three sets of nine shapes were scaled to consist of nearly the same amount of pixels to ensure equal luminance emission per stimulus. The shapes were derived from the experiment of Zhao and colleagues (Zhao et al., 2013). The background was grey (44.35 cd/m2) throughout the experiment. Shapes were presented on two locations on the screen; left and right (10.5°) of a central fixation cross. For each participant two out of the three sets of shapes were randomly chosen to avoid shape preference. The sets were presented as two continuous streams of two shapes (left and right) appearing at the time. The shapes were presented for 750 ms with an interstimulus interval (ISI) of 750 ms. One of the two streams was randomly structured in triplets for every participant as shown in Figure 1. The triplets were randomly presented, without appearing back to back (e.g., 456 123 789 123 456 789). In the other stream, nine shapes were randomised, not showing one shape twice in one trial. One of the streams was dark (0.2 cd/m2) and the other bright (88.5 cd/m2). Both luminance and location of the structured stream were counterbalanced across participants. This resulted in four conditions (structured stream right/left * bright/dark), equally divided over the participant (in-between subject). During this exposure phase, participants were instructed to fixate on the cross in the centre and passively watch the shapes.

After nine shapes a search task appeared (Figure 2). This was indicated by the fixation cross changing into a fixation dot. After 750 ms two *T* shaped stimuli appeared; a distractor and a target.

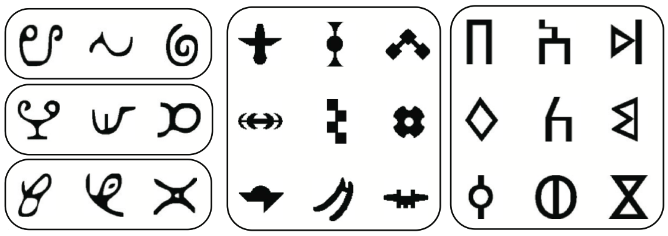

Figure 1. The three shape sets used. In this example, the left one is divided in triplets, these triplets will be presented in that order for the entire experiment. The order of the others is random.

Zhao, et al., 2013

The distractor was a normal *T,* the target had a horizontal offset of 15%, either to the right or to the left. Both were randomly presented upward or upside down and on the right or left side of the screen. Hence, the structured stream didn't predict target location or better performance. The stimuli had correlating colour with the shapes from that side of the screen. The participant had to find the target and press the right or left arrow on the keyboard to indicate the direction of the offset. The stimuli were presented for 750 ms, with a minimum ISI of 750 ms. The screen remained blank until a key was pressed. To evaluate the response, the fixation dot turned green if correct and red if not. Participants were instructed to respond as fast and accurate as possible and it was allowed to fixate on search task stimuli. This was the end of one trial.

The experiment consisted of 75 trials and took about 25 minutes. After the experiment, the participants were debriefed. First, they were asked if they noticed anything out of the ordinary about the shapes. Second, if they noticed some order in the way the shapes appeared. Finally, the participant were told about the triplets and asked if they could point out which side was structured.

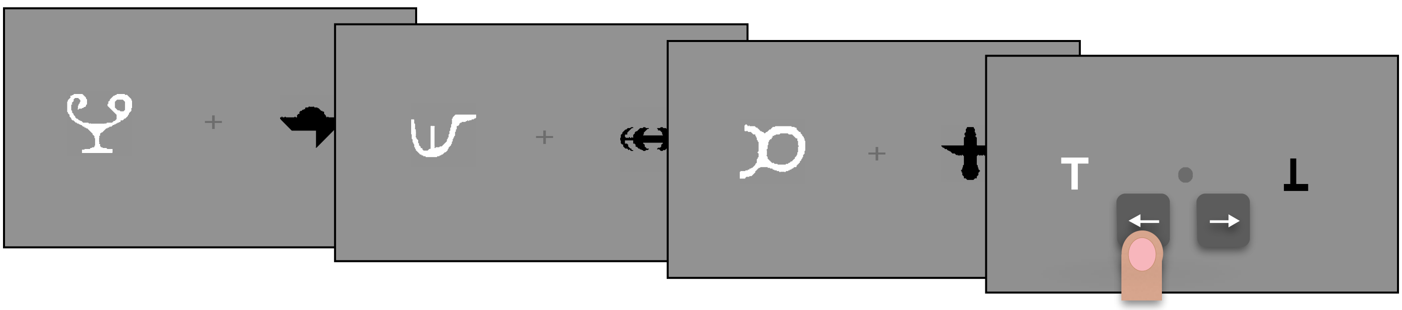

Figure 2. Example scheme of experiment. Chronology from left to right. Three shape presentations are shown in stead of the normal nine shape presentations per trial. In this example the left, bright side is structured in the order shown in Figure 1. The fourth window represents the search task. Target present on right side of the screen, offset 15% to the left. Correct answer: left arrow.

Results

Behavioural Results

Trials (43%) were excluded when participants fixated 3.3° (100 pixels) away from the fixation cross in the centre of the monitor. The amount of trial exclusion was extremely high, therefore we tried a wider margin (4°) for the maximum angle of fixation. The new angle, however, still resulted in an exclusion of 40,3% of the trials. We observed some individual trials and found that in most excluded trials, the participants looked at the symbol streams. In further analysis we used the 3,3° angle data. Twenty-six trials with a reaction time above 3000 ms were excluded. Except for three of these trials, all outliers were present in the first trials of the experiment, when participants still had to get familiar with the experiment. This resulted in 1035 trials remaining. In reaction time analysis, all incorrect response trials (13,3%) of the 1035 trials were excluded.

For reaction time data, different conditions were used, because the luminance variable doesn't effect the behavioural data. The reaction times and accuracy were researched within subjects. The two conditions were: target presented on the same side as the structured stream (on-target condition) and target presented on the side of the random stream (off-target condition). A lower reaction time and higher accuracy in the on-target condition would demonstrate the attentional bias of statistical learning. We averaged the reaction times of all participants for both conditions and found a mean reaction time on the on-target condition of 1750 ms and on the off-target condition of 1782 ms. This did not show a significant difference in a paired sample t-test, $t(24) = -0.64$, $p = 0.53$. Also the difference in accuracy was not significant, $t(24) = -1.25$, $p = 0.22$. This is contrary to the findings of Zhao, et al. (2013)

Pupil size data

Trials with maximum gaze overshoot were excluded, but incorrect trials and outliers were included in pupil analysis. The four groups of participants, were combined to two conditions: the structured side was bright (bright condition) or dark (dark condition). From both conditions, we took the average pupil size of all the remaining trials (1061) and plotted them over the duration of one trial. We hypothesised that the mean pupil size per trial would be higher for the dark condition. Figure 3a shows the difference in pupil size between the two conditions. We used an independent samples t-test on the average pupil size per participant. This difference between the dark and bright condition is not significant with a mean p-value of 0.45, shown in the bottom graph of figure 3a.

The pupil size over time data was derived by taking the average pupil size per trials for both conditions. Both bright and dark conditions are shown in Figure 3b, with the moving average and polynomial lines. The bright condition shows a slowly declining line, which in the end slowly rises. The dark condition also declined at the beginning, but quickly starts to rise. The rise and decrease are very minimal. No statistical analysis was performed, but the pattern that has been observed doesn't show a consistent or strong effect.

Participant report

When asked about the order of the shapes, none of the participants reported noticing temporal regularities in the experiment. After they were told about the regularities only five participants reported noticing the triplets. From these five, only one could tell the correct location of the structured stream.

However, after telling the participants about the location of the structured stream, 12 participants reported they noticed looking more often at that side of the screen. Every time just before the search task they would make a fixation to the structured stream. Some of them became aware of this during the test and a few suppressed this urge and deliberately looked the other way.

To investigate if the participants were looking to the side of the structured stream more often, we took the maximum gaze deviation per trial per participant. The deviations to the left of the screen were below zero and the deviations to the right above zero. All trials were used but the first two trials of each participant, resulting in 1752 trials. In the first two trials statistical learning is not likely to occur after just a few repetitions of the regularities (Turk-Brown et al., 2009). We averaged al the individual trials. The average when the structured side was presented on the left was: -18.14. The average when the structured side was presented on

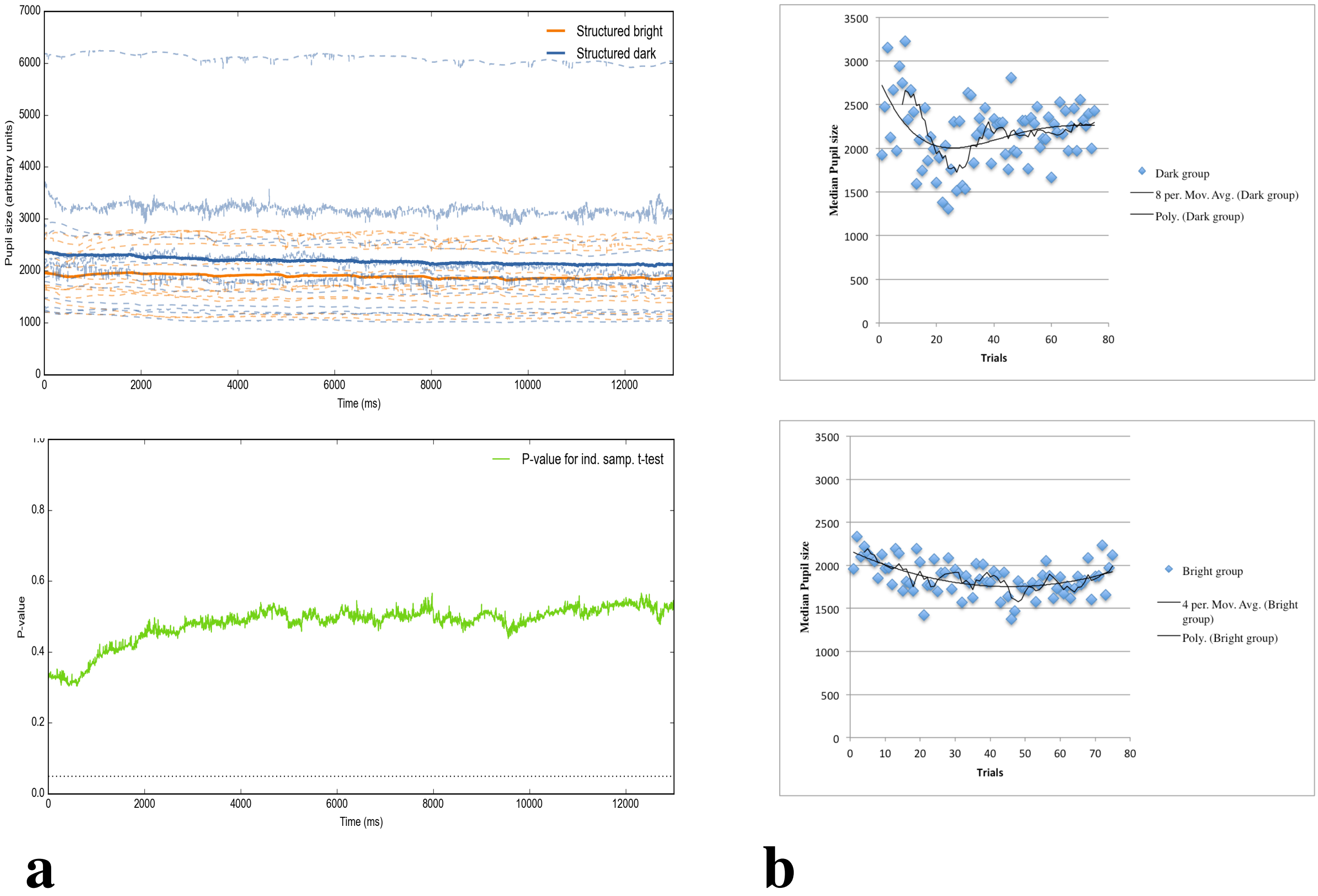

Figure 3. a) Mean pupil size for all trials[1], p-value[2], b) median pupil size per trial for dark[1] and bright[2] group. Thin lines in a[1] represent mean pupil size of all trials for individual participants, thick line represents average of all participants. Blue dots in b[1,2] stand for average median pupil size for each trial. b[1] smooth line represents a polynomial line of the second order and an eight period moving average trend line. b[2] polynomial of the fourth order and four period moving average trend line.

the right was: -16.43. This implies that the participants in all trials averagely looked more to the left. This implies that if the structured side was right, the participants looked more to the non-structured side. However, if the structured side was presented on the left side, the participants looked more to the structured side. Furthermore, we counted the individual trials with gaze towards the structured side and towards the non-structured side. We found that in 848 trials the participants looked to towards the structured side and in 910 trials the participants looked towards the non-structure side. This contradicts our hypothesis. We also compared the trials with a gaze direction above the original threshold of 3.3°, because a saccade below the threshold was not considered as a gaze. In 361 trials the participants gazed towards the structured side and in 410 trials the participants gazed towards the non-structured side of the screen. Again, this falsifies our hypothesis. Hence, in this analysis, no statistical learning was observed. The observation from the participants that they were looking to the structured side of the screen more often, did not lead to enough power to influence the results or the conscious awareness of this observation pushed the results in the other way.

Discusion

The purpose of the experiment was to show statistical learning occurred and temporal regularities indeed bias attention to a spatial location over noisier locations. This would be accompanied by measuring a pupillary response, showing that the observed overt attentional shifts

(Zhao et al., 2013) are preceded by covert attentional shifts to the biased location. Furthermore, the pupil size over time could give inside in the learning process and time it took for attentional effects to emerge from statistical learning. In spite of finding data that pointed in the right direction for all these hypotheses, no significant results were observed.

Focussing on the behavioural data, the fact that no significant results were found is at odds with earlier findings. Taken into account that Zhao and colleagues did find significant data in a highly similar experiment, the lack of equivalent data must lie in the differences in design and/or execution of our experiment. In the execution of our experiment, one factor did play a crucial role. As reported, 43% of the trials were excluded due to maximum gaze overshoot. This eliminated almost half of our data, which obviously leads to less power. The design of our experiment deviates on two factors. First, we only used two shape streams to implement the difference in luminance. This could have led to more awareness of the regularities, but only one out of twenty-five reported the correct location of the structured stream. However, the fact that nearly half of the participants noticed themselves fixating to one specific side during the search task, could reflect awareness of the effects of statistical learning. This conscious shift of attention could have influenced the results. This, however, is purely speculation. Especially because some consciously resisted the attentional bias and thereby negated the effect. Second, our experiment didn't contain a forced choice test to validate if triplets received explicit preference over three random shapes. This did not influence the reaction time data, but it could have supplied us with data proving statistical learning did occur.

The pupil data is obviously correlated with the behavioural data. Therefore, all arguments for not finding significant behavioural data apply for the pupil data. Besides these explanations, there are more reasons the pupil data was not significant. Pupil size is not exclusively influenced by light and attention. Other factors such as arousal influenced the pupil size (Partala and Surakka, 2003). Normally, these kind of variations are filtered out by the sample size of the experiment. In this case, however, we have used a between-subject analysis and the effect was not very strong in the behavioural data. 'Outside' influences could have caused these results. Moreover, the interpersonal differences in pupil size could be a problem in the experiment. Since we couldn't measure a baseline pupil size, some people can cause outliers in their pupil size. Again, this should be filtered out by the sample size. In addition, a within-subject design could have solved this.

In the pupil size over time, some external effects could explain the trend lines observed. Both graphs show a rapid decline in the first trials. Additionally, they both start with a relatively high pupil size. For the graph of the bright group, this would confirm the findings of Turk-Brown and colleagues, by seeing effects of statistical learning after the first few repetitions (Turk-Brown et al., 2009). However, the other graph also starts with a rapid decline which stops descending after approximately 20 trials (4.5 minutes). An explanation for the decline of both graphs could be the dark adaption of the eye at the start of the experiment. Before the experiment, the lights in the lab are on, which bleaches the photoreceptors of the eyes. When the experiment starts, the light is turned off. The photoreceptors take some time to adapt to the change in light intensity. To compensate for this decline in vision, the pupils dilate. This effect declines after 5-10 minutes when the eyes are considerably adapted (Barlow, 1972). This explains the rapid decline at the start. After 5 minutes the graphs of the dark and bright groups increase and decline, respectively. As recorded by Zhao and colleagues, the second half of the experiment, shows less effects of statistical learning (Zhao et al., 2013). Both graphs become more flat at the end and pupil size returns to an average size.

By considering the shortcomings of our experiment, the results seem promising. As mentioned, the data on all hypotheses points in the right direction. We did not disprove the theories on statistical learning, but outlined the possibilities for future research. This future research should involve a more similar design as the experiment of Zhao et al. Besides, when measuring pupil size, a within-subject design is more suitable. In addition, the experiment should be executed more accurately. Trying to avoid as many trial exclusions by pushing the participants to focus on the centre of the screen. Further research should focus especially on the pattern in time of statistical learning. The fact that we found an interesting pattern, without finding sufficient other data, suggests that this is an interesting topic to research. Furthermore, finding the time factors of statistical learning, enables other research or development to use this knowledge for practical purposes.

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