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# **Does surprise enhance infant memory? Assessing the impact of the encoding context on subsequent object recognition**

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**Keywords:** surprise, recognition memory, pupillometry, mislabelling, enhanced learning

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## **Abstract**

A discrepancy between what was predicted and what is observed has been linked to increased looking times, changes in brain electrical activity, and increased pupil dilation in infants. These processes associated with heightened attention and readiness to learn might enhance the encoding and memory consolidation of the surprising object, as suggested by both the infant and the adult literature. We therefore investigated whether the presence of surprise during the encoding context enhances subsequent encoding and recognition memory processes for the items that violated infants' expectations. Seventeen-month-olds viewed 20 familiar objects, half of which were labelled correctly, while the other half were mislabelled. Subsequently, infants were presented with a silent recognition memory test where the previously labelled objects appeared along with new images. Pupil dilation was measured, with more dilated pupils indicating (1) surprise during those labelling events where the item was mislabelled and (2) successful retrieval processes during the memory test. Infants responded with more pupil dilation to mislabelling compared to correct labelling. Importantly, despite the presence of a surprise response during mislabelling, infants only differentiated between the previously seen and unseen items at the memory test, offering no evidence that surprise had facilitated the encoding of the mislabelled items.

**Keywords:** surprise, recognition memory, pupillometry, mislabelling, enhanced learning.

## **Introduction**

The idea that infants are active learners who systematically select information for further exploration and learning has gained support from studies showing that infants preferentially attend to novel stimuli as a function of its complexity (Aslin, 2007) and that they learn better about objects that they themselves have chosen as a source of further information (Begus, Gliga & Southgate, 2014). In addition, infants have been shown to increase their sampling of visual and auditory stimuli that have an intermediate level of complexity, reducing their exploration to both minimally and maximally complex input (Kidd, Piantadosi & Aslin, 2012; 2014). In light of infants' limited capacity to process new information, stimulus novelty and the relative uncertainty of event sequences might drive their allocation of attention to stimuli that is neither perfectly predictable, nor impossible to learn from.

In accordance with the idea that a certain degree of complexity enhances learning, a categorization study showed that infants learnt best when the perceptual distance across consecutive exemplars was increased (Mather & Plunkett, 2011). A computational model using the same stimuli set has shown further learning benefits when the model chose successive stimuli that maximised the feature distance between the new stimulus and the previously encoded one (Twomey & Westermann, 2018). Although larger information gaps temporarily increase the uncertainty in the environment, they might facilitate learning by triggering cognitive processes that are directed at closing these gaps.

Violations of prior predictions might thus play a special role in learning by highlighting a new piece of information and facilitating the revision of the learner's current set of expectations. Early studies in developmental research have shown that both infants (Charlesworth, 1966) and primary school children (Charlesworth, 1964) continued an experiment longer and completed more trials in the conditions where their prior predictions were overwritten by unexpected events. In addition, pre-schoolers have been found to increase

their exploration of toys that have previously violated their expectations (Bonawitz et al., 2012; Cook, Goodman & Schulz, 2011), possibly indicating that longer looking times in the traditional violation of expectation paradigms (Baillargeon, 1986; Baillargeon, Spelke & Wasserman, 1985; Wynn, 1992) reflect infants' attempt to visually explore the event outcome that contradicted their expectations. Furthermore, the magnitude of surprise measured by pupil dilation has been linked to the strength of infants' prior predictions (Gredebäck et al., 2018; Juvrud et al., 2019), indicating that the mismatch between infants' expectations and the event outcome creates an error term, which is then fed back into the cognitive system.

Violations of strong pre-existing predictions has also been linked to learning in 12-month-old infants in a study that showed superior learning following scenarios that contradicted the laws of object solidity and spatiotemporal continuity (Stahl & Feingenson, 2015). Infants who saw an object go through a wall or appear from a distant location in the scene successfully learnt a new, unrelated property about the object, while infants who witnessed no such violation did not map the same properties onto the object. A follow-up study with pre-schoolers has also shown that children learnt a novel word only when the object had previously defied their knowledge of physical laws by unexpectedly appearing from a new location following a hiding event, suggesting that surprise facilitates learning when the information would otherwise be forgotten (Stahl & Feingenson, 2017).

The effect of surprise on learning might be explained by a heightened attentional state and an increase in arousal levels, which have been shown to enhance memory consolidation and recall in adults (Bradley et al., 1992; McGaugh, 2004). Arousal seems to enhance memory through an increase in noradrenaline levels facilitating the consolidation of the newly acquired information of high salience or emotional significance (McGaugh, 1990; Roozendaal & McGaugh, 2011). Such arousal related increases in noradrenaline are directly correlated with an increase in pupil dilation (Preuschoff, Hart & Einhäuser, 2011; Bradley et al., 2008), offering

a single measure for the cognitive mechanisms underlying both surprise and enhanced encoding.

Furthermore, the violation of a prior prediction might increase the uncertainty in the environment, which has been linked to higher learning rates in adults where participants had to dynamically update their predictions in light of unexpected information (Nassar et al., 2012; McGuire et al., 2014; O'Reilly, 2013). Therefore, the uncertainty resulting from a surprising event might increase the amount of cognitive effort deployed to explore and analyse the unexpected event outcome, which in turn might result in deeper encoding and better memory for the surprising item. In accordance with the idea that pupil size is a reliable measure of cognitive effort (Hess & Polt, 1964; Granholm et al., 1997), increased pupil dilation during encoding has been associated with enhanced memory performance in both adults (Goldinger, He & Papesh, 2009; Papesh, Goldinger & Hout, 2012) and infants (Cheng, Káldy & Blazer, 2019; Káldy & Blazer, 2020).

Changes in arousal levels and/or cognitive effort indicated by increased pupil dilation have been suggested to be mediated by a change in attentional processing systems, with more dilation linked to an increase in focused attention to task-relevant stimuli (Laeng, Sirois & Gredebäck, 2012; Aston-Jones & Cohen, 2005). Time-locked increases in pupil dilation have thus been interpreted as 'interrupt signals' or 'network-reset signals' that indicate a switch in attentional resources when detecting a new target or event (Bouret & Sarah, 2004; Dayan & Yu, 2006). Therefore, if surprise is associated with increased cognitive effort and arousal, which is mediated by an increase in focused attention, pupil dilation following the surprising event might be an index of the depth of encoding and the likelihood of the successful retrieval of these events.

In the current study we investigated the effect of semantic violations on subsequent recognition memory by presenting 17-month-olds with a sequence of familiar images, half of

which were labelled correctly, while the other half were mislabelled. Pupil diameter was measured to establish whether infants responded to the mismatching labels with more dilation compared to the matching labels. Following the naming events, infants saw the previously labelled images along with previously unseen images of familiar objects. Pupil dilation was then used as the measure of recognition memory, with more dilation indicating stronger memory for those objects.

Pupillometry has been used extensively in developmental research to establish a surprise response to unexpected social and physical events (Jackson & Sirois, 2009; Sirois & Jackson, 2012; Gredebäck & Melinder, 2011; Hepach & Westermann, 2016). In the auditory domain increased pupil dilation has been observed in infants and toddlers after the presentation of deviant sounds in an oddball paradigm (Wetzel et al., 2016), in response to animal sounds that did not match the presented image (Krüger, Bartels & Krist, 2019), and following the mispronunciation of familiar words (Tamási et al., 2017; 2019; Fritzsche & Höhle, 2015). Furthermore, pupil dilation has been used as a reliable index of recognition memory in adults (Võ et al., 2008; Otero, Weekes & Hutton, 2011; Goldinger & Papesch, 2012), as well as in infants (Hellmer, Söderlund, & Gredebäck, 2018). Importantly, in the adult literature increased pupil dilation at retrieval has also been observed when the study items were presented acoustically (Otero, Weekes & Hutton, 2011), when the test items were semantically related to the study items (Montefinese, Vinson & Ambrosini, 2018), as well as when the test item was incorrectly judged as old (Kafkas & Montaldi, 2015). This evidence suggests that pupil dilation at retrieval does not simply respond to the perceptual features of the previously presented objects, but rather, it indicates the strength of the underlying memory trace.

Although pupil dilation has been used in infants both to establish the presence of surprise following violations of expectation, as well as an indicator of recognition memory, to our knowledge no study has directly explored the relationship between surprise and learning by

linking a quantifiable index of surprise to the strength of the resulting episodic memory for the object. Importantly, the studies by Stahl & Feingenson (2015; 2017) did not use a direct measure of surprise, but rather inferred its presence or absence from the differences in the dependent variable across conditions.

We predicted an increase in pupil dilation following mislabelling, indicating that infants' lexical expectations were violated. Crucially, if violations of expectation result in a more in-depth encoding of the object, infants are expected to respond with more dilated pupils to the items that were previously mislabelled compared to the previously correctly labelled items at the recognition memory test. On the other hand, if surprise does not enhance infants' memory for the mislabelled items, pupil diameter at test is expected to be different as a function of novelty, but independent of the effect of surprise concerning the previously mislabelled items.

Two different types of auditory violations were used in a between-subjects design that differed in perceptual novelty and the degree to which the violation was impossible or merely unlikely. In the Wrong Label condition familiar objects were mislabelled by a familiar but mismatching name (dog = *banana*), while in the Novel Label condition the familiar objects were mislabelled by an unfamiliar name (dog = *moxie*). While given the relevant lexical knowledge, the former scenario is impossible, the latter scenario may reflect a natural process in language acquisition whereby a previously over-extended category is gradually narrowed down to attain the correct referential scope of the word (Naigles & Gelman, 1995; Gelman et al., 1998). Furthermore, if surprise and subsequent memory enhancement are simply driven by perceptual novelty, the effect is only expected to be present in the Novel Label, but not in the Wrong Label condition.

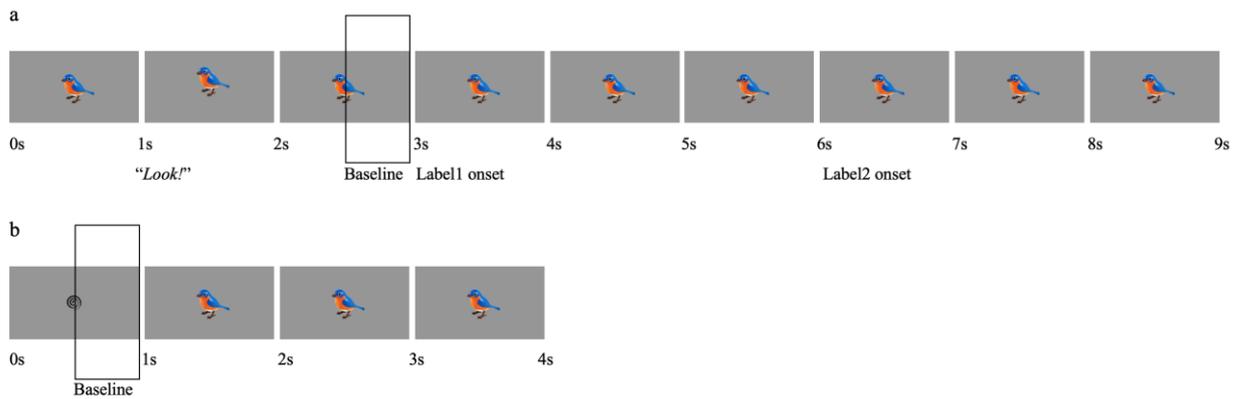
## **Methods**

### **Participants**

Forty-one typically developing, monolingual 17-month-olds were tested, 23 in the Wrong Label and 18 in the Novel Label condition. (501 – 532 days,  $M = 515.63$ ,  $SD = 10.14$ , 17 females). Infants were included if they had valid data for at least 50% of the trials in both parts of the experiment. An additional 10 babies were tested but excluded due to insufficient data. Infants were recruited from the Greater London area through the online database of the Centre for Brain and Cognitive Development, Birkbeck. The research received ethical approval from the Ethics Board of Birkbeck, University of London and complied with the guidelines laid down in the Declaration of Helsinki. Written informed consent was obtained from parents or guardians prior to the testing sessions.

### **Stimuli**

Thirty names of familiar objects were selected using Wordbank (Frank et al., 2017). An item was selected if at least 60% of infants understand it at 17 months of age according to the data based on the Oxford CDI (Flocchia, 2017). Thirty phonologically legitimate non-words were generated that were matched to the familiar names in consonant-vowel structure and syllable length using a pseudoword generator (Keuleers & Brysbaert, 2010). Images corresponding to the familiar labels were selected from the stimuli set of two previously published papers on word learning (Bergelson, 2012; 2018) and matched for brightness and saturation using Final Cut Pro. The correct and incorrect labels as well as the corresponding images are displayed in the Supplementary Materials (Table S4). The sequence of the Labelling and Recognition memory trials are depicted in Figure 1.



*Figure 1.* Labelling (a) and Recognition memory test (b) sequences. a) Labelling: The image of a familiar object appeared in the centre of the screen (0s), and it wobbled while the voice said “Look!” (1-2s). Following that the object remained stationary during the two labelling events (3s, 6s). The 500ms interval preceding the onset of the first label was used as a baseline for measuring changes in pupil dilation in response to the labelling events. b) Recognition memory: Following a central fixation stimulus (0-1s) the image appeared in the centre of the screen for 3s (1-4s) with no visual changes and no auditory stimuli during the trial. The 500ms of the fixation stimulus preceding the onset of the test image was used as a baseline to measure changes in pupil dilation in response to the presentation of the object.

### *Labelling*

Each infant was presented with 20 naming events. On each trial a familiar object appeared in the centre of the screen (visual angle:  $11^{\circ} 39' 0.45''$ ) on a grey background (R: 150, G: 150, B:150). The object wobbled slightly (1s-2s) while a pre-recorded female voice said “Look!” in infant directed speech. Following this, the object remained stationary, and the voice labelled the object twice, either with a matching or a non-matching label, depending on the condition.

The two labelling events started at 3s and 6s following the onset of the image, and each utterance lasted approximately 1s. Each label had been recorded twice for each object so that the trial resembles a natural naming event. The two instances of each label always appeared in the same order across babies. Each trial lasted 9 seconds. Trials were separated by a 1s interstimulus interval while a grey screen was presented along with a brief auditory stimulus to orient the infant’s attention to the next trial.

### *Recognition memory test*

Following the labelling events, 30 familiar objects were presented during a silent recognition memory test. Each object was preceded by a central fixation stimulus presented for 1s. The luminosity of each fixation stimulus was matched to the subsequent test image.

Following this, the object appeared in the centre of the screen on a grey background and remained stationary for 3s. Each trial lasted 4s. After every 5 trials a short video was played for a maximum duration of 30s to maintain the infant's interest in the trials.

### **Design**

Infants were randomly assigned to either the Wrong Label or the Novel Label group. During the first half of the experiment infants were presented with 20 naming events where a familiar object was labelled. Half of the objects received the matching, familiar label (Bird labelled *Bird*), while the other half of the objects received an unmatching, familiar label (Bird labelled *Car*) or an unmatching, novel label (Bird labelled *Costet*), depending on the group. The order of correct and incorrect labelling, as well as the pairings between objects and incorrect labels were randomised across the trials.

Following the naming events, infants saw a silent recognition memory test where all the objects presented at labelling appeared with 10 new objects. The order of the 30 images was randomised across the memory test. The identity of correctly labelled, incorrectly labelled and novel images were randomised across infants.

### **Procedure**

Infants were tested in a quiet, dimmed room (4.5 lx). Parents were given dark glasses and they were instructed not to interact with their infants throughout the experiment. Stimuli was presented on a Tobii TX300 eye-tracker using Matlab at a sampling rate of 120Hz. The

labelling and the recognition memory test were presented in succession, and participants did not take breaks during the experiment. If the infant was inattentive, auditory and/or visual attention getters were presented for a few seconds during both parts of the experiment. Stimulus presentation was resumed once the infant attended to the screen again. The experiment lasted approximately 10 minutes including calibration.

### **Data Pre-processing and reduction**

Linear interpolation was applied to the pupil data corresponding to each eye with a maximum gap of 10 missing samples (83.33ms). Pupil baseline was established as the 500ms of the stationary image preceding the onset of the first label in the labelling trials, and the 500ms of the fixation image preceding the onset of the test image in the recognition memory trials. Trials were excluded if there was no valid data for either of the eyes for at least 60% of both the baseline and the test intervals after interpolation. Included trials were baseline corrected by subtracting the mean baseline values for each eye from the pupil data of the corresponding eye in the test intervals. Missing data from one eye was replaced with data from the other eye, and the data was subsequently averaged across the two eyes.

The relatively narrow interpolation window and the criterion of 60% valid data within a single trial after interpolation were chosen as a conservative threshold for retaining trials for further analyses. In order to test whether our results are robust after interpolating larger gaps in the data, we ran the same analyses with a 300ms interpolation window, which resulted in the retention of 99 and 35 additional trials during the labelling and the memory intervals, respectively. The conclusions drawn from these results, displayed in the Supplementary Materials, are identical to the findings presented in our main analyses below.

Infants were excluded if they did not contribute at least 10 trials during the labelling phase ( $n = 7$ ) and at least 15 trials in the memory phase ( $n = 3$ ). These criteria correspond to,

on average, 5 trials per condition and 50% of the entire stimulus set in each phase. Each participant contributed at least 3 trials to each condition in both parts of the experiment. Infants contributed a total of 712 trials during labelling ( $M = 17.36$ ,  $SD = 2.6$ , Correct labelling:  $M = 8.83$ ,  $SD = 1.56$ , Mislabelling:  $M = 8.54$ ,  $SD = 1.51$ ) and a total of 904 trials during the recognition memory test ( $M = 22.04$ ,  $SD = 3.85$ , Previously correctly labelled:  $M = 7.12$ ,  $SD = 2.17$ , Previously mislabelled:  $M = 6.78$ ,  $SD = 1.75$ , New:  $M = 8.15$ ,  $SD = 1.49$ ).

Two intervals of interest were identified: (i) the 6s following the onset of the first label until the end of the trial during the labelling phase (0s: Label1 onset, 3s: Label2 onset), and (ii) the 3s following the onset of the test image in the recognition memory phase.

In order to assess whether pupil dilation differed reliably as a function of condition during these intervals, and to examine the time course of the effects in a data-driven fashion, a permutation analysis was conducted on the pupil data in the two intervals of interest (R, package: *permutes*,  $np = 1000$ ). During the permutation analysis, the condition labels are randomly reassigned to the data numerous times at a given time point, and on each iteration a two-tailed  $t$ -test is conducted on this data (or an  $F$ -test in case of more than two conditions). The  $t$  values over all iterations create a distribution of test statistics values observed under the null hypothesis. The observed  $t$ -statistic using the actual condition labels is then compared to the distribution of  $t$  values derived from permutation analysis at that time point, and the difference across conditions is deemed significant if the observed  $t$  value falls outside the distribution of values that could have occurred by chance (i.e. a  $p$  value is significant at 0.05 if less than 50 out of 1000  $t$ -tests had an absolute value larger than the one observed). Permutation testing is repeated at each data point and the resulting test statistics and significance values indicate the time points where the data could not have been obtained if the mapping between the independent and the dependent variable were random. This technique has been used in previous studies analysing pupil dilation in both the infant (Hochmann & Papeo, 2014; Cheng,

Káldy & Blazer, 2019) and the adult literature (Kloosterman et al., 2015; Geng et al., 2015; Quirins et al., 2018).

Since a permutation analysis was performed at each data point throughout the intervals, multiple comparisons were corrected by adjusting the alpha level to an expected false-discovery rate of 5% using the method of Benjamini and Hochberg (1995), a technique that has been widely used to correct for multiple comparisons when analysing pupil data (Einhäuser et al., 2008; Katidioti, Borst & Taatgen, 2014; Lavín, San Martín & Rosales Jubal, 2014; Preuschoff, Hart & Einhäuser, 2011; Mill, O'Connor & Dobbins, 2016). A series of consecutive significant  $p$  values following the correction indicates a reliable difference across conditions, as well as the time course of the effect throughout the interval of interest.

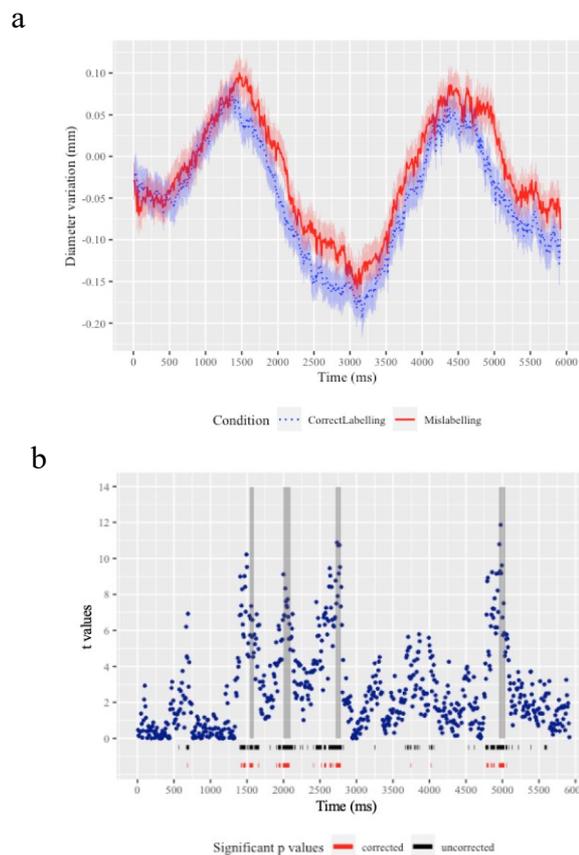
In addition, based on the results of the permutation analysis we selected a 1s analysis window within the 3s interval following the onset of each labelling event and within the 3s recognition memory phase to conduct inferential statistics. The rationale behind this analysis was to test whether the effects observed as a result of the permutation analysis are robust to changes in interval length, and also to increase comparability with previous infant studies that averaged across a larger time window when analysing pupil dilation in response to violations-of-expectation (Gredebäck & Melinder, 2010; 2011; Krüger, Bartels & Krist, 2019; Pätzold & Liszkowski 2019; Gredebäck et al., 2018) and as an index of recognition memory (Hellmer, Söderlund, & Gredebäck, 2018).

## **Results**

### *Labelling*

The pupil data during the 6s interval following the onset of the first labelling event and the  $t$  values resulting from the permutation of the data at each timepoint are depicted in Figure 2. The black line (top line) indicates the time points at which the permutation analysis yielded

a significant difference between the pupil values in the two conditions at the initial significance level of  $p < 0.05$ . The red line (bottom line) indicates the significant time points after correcting for multiple comparisons ( $p < p_{FDR=0.05}$ ). The grey rectangles indicate the intervals where corrected p values remained significant throughout consecutive time points for at least 50ms. The presence of a multiple series of significant p values indicated reliable differences in pupil dilation between the two labelling conditions that were sustained throughout at least 50ms after approximately 1.5s, 2s and 2.5s of the onset of the first label (1533-1591ms, 2008-2091ms, 2716-2791ms) and approximately 2s after the onset of the second label (4950-5033ms).



*Figure 2.* Pupil dilation following correct labelling and mislabelling. a) Changes in baseline corrected pupil diameter as a function of condition.  $T=0$  corresponds to the Label1 onset and  $t=3$  corresponds to the Label2 onset. Error bars represent the standard error of the mean. b) Results of the permutation analysis indicating significant differences across conditions at each time point (black line/top line: uncorrected, red line/bottom line: following Benjamini & Hochberg correction for multiple comparisons). The shaded areas represent the time points where consecutive corrected p values remained significant for at least 50ms.

Based on the results of the permutation analysis, infants' pupil data in each condition was averaged within the intervals corresponding to the 1.5-2.5s following the onset of each label (1500-2500ms and 4500-5500ms) in order to test whether this effect is reliable throughout a 1s analysis window. The selection of these time windows also allows for the effects of the two labelling events to be tested after the same latencies. This is a more parsimonious approach than postulating a difference between the time course of the two effects.

Average pupil values in the two conditions measured in the two analysis windows were submitted to a 2 x 2 x 2 mixed design ANOVA with the within-subjects variables of Window (1, 2) and Condition (Correct labelling, Mislabelling) and the between subjects variable Group (Wrong Label, Novel Label). The ANOVA yielded a significant main effect of Condition,  $F(1,39) = 4.68$ ,  $p = 0.037$ ,  $\eta^2 = 0.107$ , with more dilated pupils after mislabelling ( $M = 0.007$ ,  $SE = 0.022$ ) compared to correct labelling ( $M = -0.033$ ,  $SE = 0.022$ ). In addition, there was a significant main effect of Window,  $F(1,39) = 4.74$ ,  $p = 0.036$ ,  $\eta^2 = 0.108$ , with more dilated pupils in the second window ( $M = 0.001$ ,  $SE = 0.023$ ) compared to the first window ( $M = -0.026$ ,  $SE = 0.019$ ), irrespective of condition. No other effects were significant.

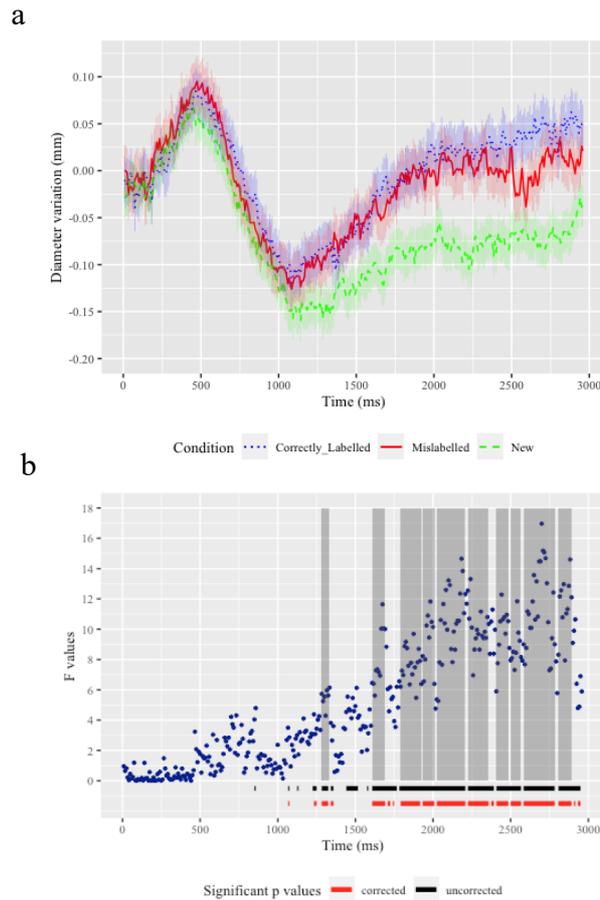
The permutation analysis, as well as the results of inferential statistics confirmed that mislabelling a familiar object with either a mismatching familiar name or an unrelated, novel name elicits increased pupil dilation, suggesting that infants' lexical expectations were violated.

In addition, pupil responses to mislabelling and correct labelling were tested using mixed effects models with Participant and Object as random factors. These models also account for the possibility that infants' familiarity with the objects and the labels may have affected their pupil dilation. In summary, all our findings using mixed models support the hypotheses presented above, and the findings are closely aligned with the results of the ANOVA. These models are reported in the Supplementary Materials.

### *Recognition memory test*

In order to establish whether recognition memory processes could have been influenced by looking time differences during the Labelling phase, a 2 x 2 ANOVA was conducted on infants' total looking time following the onset of the first label during the labelling trials with the within subjects variable Condition (Correct labelling, Mislabelling) and the between subjects variable Group (Wrong Label, Novel Label). The ANOVA yielded a main effect of Group,  $F(1,39) = 4.861$ ,  $p = 0.033$ ,  $\eta^2 = 0.111$ , with longer looking times in the Wrong Label group ( $M = 5327.44$ ,  $SE = 93.17$ ) compared to the Novel Label group ( $M = 5017.39$ ,  $SE = 105.32$ ), irrespective of Condition. No other effects were significant. Importantly, there was no significant difference between infants' looking time to the images that were labelled correctly compared to the images that were mislabelled,  $F(1,39) = 1.99$ ,  $p = 0.166$ ,  $\eta^2 = 0.049$ , Correct labelling:  $M = 5227.17$ ,  $SE = 81.17$ , Mislabelling:  $M = 5117.67$ ,  $SE = 79.44$ .

In order to investigate whether infants' memory was enhanced for those objects that were previously mislabelled, permutation analysis was performed on the pupil data during the Recognition memory phase using the 3s of the still image following baseline, as described above. Pupil dilation in response to the three conditions during the memory phase and the  $F$  statistics with the corresponding significance values at each time point are displayed in Figure 3.



*Figure 3.* Pupil dilation in response to the three conditions: previously correctly labelled, previously mislabelled, new. a) Changes in baseline corrected pupil values in the three conditions. T=0 corresponds to the image onset. Error bars represent the standard error of the mean. b) Results of the permutation analysis performed at each time point (black line/top line: uncorrected, red line/bottom line: following Benjamini & Hochberg correction for multiple comparisons). The shaded areas represent the time points where consecutive corrected p values remained significant for at least 50ms.

As with the labelling trials, a 1s analysis window was selected to confirm that pupil dilation differed across conditions and to compare infants' responses to the previously correctly labelled, previously mislabelled and new images. Based on the results of the permutation analysis, the pupil data between 2-3s after the onset of the images was submitted to a 3 x 2 ANOVA with the within-subjects variable Condition (Previously correctly labelled, Previously mislabelled, New) and the between-subjects variable Group (Wrong Label, Novel Label).

The ANOVA yielded a significant main effect of Condition,  $F(2,78) = 4.23$ ,  $p = 0.018$ ,  $\eta^2 = 0.098$ . Bonferroni corrected pairwise comparisons revealed a significant difference between previously correctly labelled and new items ( $p = 0.017$ ) and between previously

mislabeledled and new items ( $p = 0.047$ ), with no difference between the previously correctly labeledled and mislabeledled items ( $p = 1.000$ ). (Correct:  $M = 0.013$ ,  $SE = 0.025$ , Mislabeledled:  $M = 0.002$ ,  $SE = 0.027$ , New:  $M = -0.075$ ,  $SE = 0.022$ ). The ANOVA also resulted in a main effect of Group,  $F(1,39) = 5.86$ ,  $p = 0.02$ ,  $\eta^2 = 0.131$ , with more dilated pupils in the Wrong Label ( $M = 0.019$ ,  $SE = 0.021$ ) compared to the Novel Label group ( $M = -0.059$ ,  $SE = 0.024$ ), irrespective of Condition. No other effects were significant.

Similarly to the pupil dilation data during labelling, we tested infants' responses during the recognition memory phase using mixed effects models with Participant and Object as random factors. These results are displayed in the Supplementary Materials, and the findings are closely aligned with the results of the ANOVA reported above.

In order to directly investigate the differences in recognition memory between the previously mislabeledled and correctly labeledled items, we compared the memory scores in these two conditions with a two-sided Bayes Factor  $t$ -test ( $BF_{10}$ ) using a JZS prior = 0.707 (R, package: *BayesFactor*). The resulting Bayes factor of  $BF_{10} = 0.180$  indicates substantial evidence that the means in these conditions did not differ. In other words, the data are  $1/BF_{10} = 5.54$  times more likely to have occurred under the null than under the alternative hypothesis.

Furthermore, to test the relationship between pupil dilation after mislabelling and infants' memory for the images, we ran two correlation analyses between the difference scores in pupil size during the labelling trials in each window of interest (Mislabelling – Correct labelling in Window 1 and 2, respectively) and the difference scores at the memory test (Previously mislabeledled items – Previously correctly labeledled items). If surprise enhances memory for the item, pupil dilation during encoding is expected to be positively correlated with pupil dilation during the recognition memory test.

There was no significant association between the responses to the violation and the memory scores when using the labelling data in the first window,  $r(39) = -0.150$ ,  $p = 0.348$ . In

addition, there was a significant negative correlation between increased pupil dilation following the second label and pupil dilation as an index of memory,  $r(39) = -0.310$ ,  $p = 0.049$ . However, this latter finding should be interpreted with caution, as the  $p$  values are not adjusted to account for the two comparisons. In addition, we conducted the same correlation analyses on the data interpolated with a maximum tolerated gap of 300ms, which are presented in the Supplementary Materials, and we found no association between infants' pupil dilation following correct and incorrect labelling and their memory scores in response to these items.

Overall, the correlations indicate the absence of a positive relationship between the pupil values used to assess the effect of surprise and the pupil values used to assess recognition memory at test.

## **Discussion**

In this experiment we tested whether infants' surprise response elicited by the violation of their lexical knowledge can be linked to their subsequent memory for the objects using pupil dilation as an index of both surprise and recognition memory.

Our main goal was to investigate whether the increased arousal, greater cognitive effort, and ultimately an increase in focused attention elicited by the incorrect labelling events enhanced the processing of the surface features of the mislabelled items. The unexpected label in the mislabelling condition might have also elicited a motivation in infants to reassess their category knowledge and attempt to resolve the conflict between the label and the referent. Although these processes may have occurred, they are not strictly necessary for infants to show better memory for these objects, but an increased attention following mislabelling alone could have resulted in a memory advantage.

Firstly, we replicated the findings of earlier literature suggesting that infants respond to violations of expectation with increased pupil dilation (Jackson & Sirois, 2009; Sirois &

Jackson, 2012; Gredebäck & Melinder, 2011; Tamási et al., 2017; 2019; Fritzsche & Höhle, 2015). These responses measured in pupil diameter might signal an increase in arousal levels, greater cognitive effort, or an increase in focused attention when processing the mislabelled items.

In accordance with previous studies, the presence of a surprise response in the Wrong Label group indicates that pupil dilation is not merely an index of stimulus novelty, but it is also sensitive to violations that do not involve the presentation of unfamiliar stimuli, but rather a mismatch between two perceptually familiar items.

Interestingly, a previous study with 30-month-olds did not find differences in pupil dilation to correct compared to mismatching familiar labels or non-words (Fritzsche & Höhle, 2015). In our study we used infant-directed speech (“*Look!*”) combined with the contingent movement of the object at the beginning of the trial, which might have helped infants form the referential link between the label and the object, whereas in the above study the object remained stationary throughout the trial. However, it is also possible that by 30 months of age toddlers’ lexical expectations are already firmly established, which might prevent them from associating the label with the object, or it might result in the outright rejection of the mismatching label. This explanation is in line with the idea that learners allocate their attention to events that have an intermediate complexity (Kidd et al., 2012; 2014), possibly discarding new information if the discrepancy between the prediction and the outcome exceeds a certain threshold.

Secondly, we replicated previous findings in the adult (Võ et al., 2008; Otero, Weekes & Hutton, 2011; Goldinger & Papesh, 2012) and in the infant literature (Hellmer, Söderlund, & Gredebäck, 2018) showing that participants respond with increased pupil dilation to previously seen compared to unseen items. In this experiment, a single, brief presentation of 20 items elicited reliable differences in infants’ recognition memory between previously seen and unseen items, offering an insight into episodic memory performance at 17 months of age.

Crucially, despite evidence of increased pupil dilation in response to mislabelling, we found no difference in pupil size during the recognition memory test that would indicate that infants had better memory for those items that had previously violated their expectations. This finding is at odds with adult studies using similar paradigms that suggest enhanced memory for items that were encoded under surprising or arousing circumstances (McGaugh, 1990; Vö et al., 2008; Nassar et al., 2012; Roozendaal & McGaugh, 2011).

Importantly, our results do not support the hypothesis previously proposed by Stahl & Feingenson (2015; 2017) that violations of expectation enhance learning about the surprising object. However, there are a few important differences between our design and the paradigms used by Stahl & Feingenson (2015; 2017), which might have contributed to the lack of evidence to support a link between surprise and improved learning. Firstly, in our study the trials that accorded with infants' expectations and those that violated them were presented equiprobably in a random order; therefore, the overall uncertainty regarding a subsequent violation was essentially maximised. Studies with adults suggest that the anticipation of uncertainty, as well as the infrequent violation of a previously generated set of predictions has the most robust effect on learning (Nassar et al., 2012; McGuire et al., 2014). In line with this reasoning, the repetition of surprising events might also impair the resulting encoding benefit. Although we found strong evidence for the presence of a surprise response throughout the experiment, presenting fewer surprise trials may have been more effective in increasing infants' memory performance.

Importantly, the above studies that suggest a link between surprise and learning in infants and pre-schoolers (Stahl & Feingenson, 2015; 2017) used single trials in a between-subjects design that left no room for the participant to accommodate to the uncertainty of the experimental setting. In contrast, our design was chosen in a way to disentangle the effect of the infrequency of the stimuli from the effect of surprise itself. On the one hand, it is possible that infants did not encode the surprising items better due to the repetition of the violations,

while on the other hand they may have shown increased encoding for both types of items due to the relative uncertainty of the environment. Future studies investigating the role of surprise in learning should attempt to disentangle the individual effects of violations of expectation from the underlying change in cognitive mechanisms that occur throughout the experiment.

Although surprise may have enhanced the encoding of both types of items to a certain extent, the large number of the images and the short presentation times make it highly unlikely that infants' overall memory performance was at ceiling. Earlier studies with pre-schoolers using similar set sizes of items in recognition memory tasks did not find performance to be at ceiling even at 3 years of age (Parkin & Streete, 1988; Balcomb & Gerken, 2008). Therefore, the lack of a difference between the previously correctly labelled and mislabelled items at the memory test cannot be explained by a near perfect learning of the entire stimulus set. In addition, pupil dilation is a reliable index of the strength of the underlying memory trace, rather than a binary measure (Otero, Weekes & Hutton, 2011; Montefinese, Vinson & Ambrosini, 2018; Kafkas & Montaldi, 2015), therefore, a memory enhancement for the surprising items could have been observed even if the correctly labelled items were also remembered to some degree.

In summary, although our study offers positive evidence regarding infants' detection of semantic violations, as well as the presence of recognition memory processes, we found no evidence for a positive relationship between infants' surprise response and their memory for these objects. In contrast, we found a negative correlation between pupil dilation after mislabelling and pupil diameter in response to the image during the recognition memory test. However, this association was only observed using one of the analysis windows, and the significance value was not corrected for multiple comparisons. Future studies should investigate whether certain types of surprise may hinder the encoding of the surprising material.

In conclusion, while surprise may facilitate learning and memory in some circumstances, an enhanced encoding of the object for further memory is not a necessary outcome of surprise.

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