The Role of Colour Labels in Mediating Toddler Visual Attention

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Toddlers, children and adults will spontaneously attend to a semantically- or perceptually-related object when a named target is absent from the visual scene: Upon hearing "*strawberry*", they will orient to a red plate rather than a yellow one. We examine the role that knowledge of feature labels plays in mediating visual attention to unnamed features. For example, does knowing the word "*red*", facilitate attending to red objects, though the label is not uttered? We show that toddlers systematically fixate a colour-related object, if and only if they know the name of the colour associated with the named object and the perceptually-related object. These findings suggest that knowledge of perceptual feature labels can play a central role in highlighting salient similarities between objects, both present and absent in the toddler's visual field. We discuss the implications and limitations of these findings beyond the realm of recognition of colour similarities between objects.

Keywords: Colour labels; Visual attention; Feature representation; Eye-tracking

Introduction

Individuals spontaneously attend to an object when it is named, and will even direct their attention towards objects in the visual scene that share properties with the named object (Cooper, 1974). More recently, it has been shown that both adults and toddlers attend to objects based on semantic (Huettig & Altmann, 2005; Huettig & McQueen, 2007), phonological (Allopenna, Magnuson, & Tanenhaus, 1998; Desroches, Newman, & Joanisse, 2009; Chow, Aimola Davies, & Plunkett, 2017), and shape information (Huettig & Altmann, 2004) evoked by auditory words.

One recent field of enquiry into language-mediated attention has focused on the domain of colour. Huettig and Altmann (2011) demonstrated that when adults hear a target word with a typical diagnostic colour (e.g. "*frog*"), they attend to a green object. The finding was extended to 3 year-old participants with similar results (Johnson & Huettig, 2011). These results suggest that colour knowledge is a part of the meaning of some words, for both adults and children.

While it is clear that knowledge of the typical colour of objects has the potential to mediate attention, even in young children, it is unclear how this colour information is stored and accessed in the lexical-semantic system. One possibility is *direct activation*, where the label of a typically-coloured object evokes a mental representation which directly activates a representation of the associated colour feature. Another possibility is *label-mediated activation*, where the auditory label evokes a colour *label*, which subsequently activates an abstract representation of the colour. These findings have important implications for the role of language in cognition. A label-mediated activation account suggests a top-down role for language in the cognition of colour, such that a participant cannot access the concept of colour without accessing the label. The alternative, a direct activation account, would suggest that language does not exhibit such a strong top-down effect on cognition.

In adults and children, the contrast between direct and label-mediated colour representations is difficult to operationalise behaviourally because both possibilities are potentially available to them: they know colour names *and* may represent the typical colours of objects independently of those names. However, by some accounts, very young children are slow to learn colour names (Franklin, 2006; Mervis, Bertrand, & Pani, 1995; Pitchford & Mullen, 2002; Sandhofer & Smith, 1999; Soja, 1994) and therefore offer a natural opportunity to explore whether knowledge of colour labels is necessary to direct their attention towards objects in the visual scene that share colour properties with a named object.

Johnson, McQueen, and Huettig (2011) tested 24

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month-old toddlers, who did *not* know colour labels according to both production as measured in parental report, and comprehension measured in an eye-tracking comprehension task, and discovered they also looked at an object that shared the same colour as the referent of an auditory word, e.g., the toddlers looked at the red plate upon hearing "*strawberry*." This result lends strong evidential weight to the direct access model, whereby the auditory label evokes a mental representation that encodes the associated colour feature of the target object, and activation of the associated colour feature can mediate attention towards other objects that share the same colour.

In the Johnson et al. (2011) study, participants were shown two pictures side-by-side and heard a target word on each trial. Participants were shown four target-present trials, four related distractor trials, four unrelated distractor trials, seven colour trials (used to test participants' colour word knowledge) and seven filler trials. The focus of the study was the four related distractor trials, which used labels for animals and food with typical colours. In these trials, participants saw an object matching either the colour of the object label (e.g. a red plate when hearing "*strawberry*)" or an object matching the semantic category of the object label (e.g. a sandwich when hearing "*strawberry*"), paired with an unrelated object. An analysis of these trials showed that in the second one-second interval after target word onset, participants look to both types of related distractor above chance. The semantic effect was, however, found to be stronger than the colour effect (see also Mani, Johnson, McQueen, & Huettig, 2013).

Johnson et al. (2011) also tested the colour word knowledge of participants with a preferential looking trial that used coloured smiley faces. The results suggested that only two of the colours (green and grey) were known to participants. Parents were also asked to report on children's production of colour terms and how well they were used. While 30 of the 48 participants were reported to produce some colour terms, only five were identified as being able to use the colour terms relating to the experiment. When the relevant trials from these five participants were excluded, participants still demonstrated systematic looking at the colour-related distractor. Thus, Johnson et al. concluded that colour labels did not appear to be mediating attention towards the colour-related distractors in these 24-month old toddlers, offering support for the direct activation account.

Comprehending Colour Words

The Johnson et al. (2011) study employed two measures to assess colour word knowledge: colour word comprehension according to an eye-tracking task at the end of the experiment, and colour word production as measured by parental report. First, the findings demonstrate that 24 month-old toddlers are unlikely to comprehend colour words. This claim concurs with previous reports about the timing of colour word learning (Franklin, 2006; Mervis et al., 1995; Pitchford & Mullen, 2002; Sandhofer & Smith, 1999; Soja, 1994). However, recent investigations into colour word learning in different languages suggest that in many languages, the majority of toddlers learn colour words well before their second birthday, at least according to parental reports (Forbes & Plunkett, 2018; Wagner, Jergens, & Barner, 2018)[1]. Forbes and Plunkett examined the reported knowledge of colour words in 8 – 30-month-olds across 11 different languages based on parental reports. Similarly, eye-tracking studies that examined children's knowledge of colour words have found signs of comprehension as early as around 18–19 months of age (Forbes & Plunkett, In Press, 2017; Wagner et al., 2018). This suggests that there is a possibility of toddlers possessing a very basic colour word knowledge of typical, focal examples of some colours. Additionally, the fact that *grey* was known to participants suggests other colours may have also been known, as grey is one of the last colours to be learned (Forbes & Plunkett, 2018).

Second, in the Johnson et al. (2011) study, nearly two-thirds of their participants were reported to have some knowledge of the relevant colour words for the task, since they were reported to often use these colour words incorrectly. However, colour words are probably learned in much the same way as other categories of word, in that initial production is preceded by a partial comprehension, after which comprehension and production continue to develop to a more adult-like form (Wagner, Dobkins, & Barner, 2013; Wagner, Jergens, & Barner, 2014; Wagner et al., 2018). Partial comprehension of the relevant colour terms by the toddlers in the Johnson et al. (2011) study may have been sufficient to support label-mediated attentional processes. Furthermore, parental reports of comprehension of colour terms has also been found to predict behavioural data for toddlers as young as 19-months (Forbes & Plunkett, In Press, 2017). While children do often apply colour words incorrectly, these errors are not random, and are

[1]Though it should be noted that no data was reported for Dutch—the language spoken by the participants in the Johnson et al. (2011) study.

mostly due to over-generalisation of the term. These misuses of colour words mask the fact that the focal point of the colour word is often understood correctly, so an incorrect usage of a term can often imply a comprehension of the focal colour for that term, but an inability to correctly comprehend the category boundary (Wagner et al., 2013, 2018).

The Present Study

In light of the recent findings regarding the earlier timeline of colour word learning by toddlers (Forbes & Plunkett, 2018, In Press; Wagner et al., 2018), the present study aimed to examine the generalisability of the results of the Johnson et al. (2011) study. In particular, we aimed to evaluate toddlers' performance on a similar task to that described in Johnson et al. (2011), comparing toddlers who did and did not understand the colour labels in question, using the methods reported in Forbes and Plunkett (In Press) and Forbes and Plunkett (2018). Since these studies have shown that most 24-month olds have at least a partial understanding of several basic colour terms, we also included a second, younger age group. Colour word learning in English has been shown to begin around 19 months (Forbes & Plunkett, In Press), making them an ideal comparison group to the original study cohort. Thus, in the present study, participants from two age groups were recruited; 19-month olds as well as a 24-month old age group as in the original study.

The design of the current study was similar to that of the Johnson et al. (2011) study, including target absent trials, target present trials, colour-related trials, and semantic-related trials, as well as the inclusion of a parental report on colour word knowledge. There were, additionally, two major changes to the design of the present study. First, the colour trials used to test participants' colour word knowledge were removed, as parental reports of comprehension, such as those included in the present study, are a strong predictor of tightly controlled experimental findings on colour word comprehension (Forbes & Plunkett, In Press), and thus should be adequate to assess comprehension of colour words. Second, four additional *colour only* trials were added for each participant, as used in (Johnson & Huettig, 2011). These trials were similar to the colour related distractor trials in the original study, where one of the objects had a colour in common with the target word, but the two objects shown on the screen were kept identical, except for their colour, to remove any bias stemming from a preference for one object over another. These extra trials also allow for greater power when analysing the colour related trials, and the inclusion of both types of colour trial, as well as a comparison of both, can provide further assurance that the results are not biased by the visual attractiveness of one of the objects.

We predicted that only those toddlers who understand the relevant colour labels will systematically direct their attention to colour related distractors, if attention to an object's colour feature is mediated through the colour label. In contrast, if colour labels are not a prerequisite for mediating attention to colour related distractors, then both toddlers who know the colour label and those who do not should show similar levels of systematic attention to colour related distractors.

Methods

Participants

N = 39 nineteen month-old toddlers (17 female, mean age = 19.44 months, s.d. age = 0.49 months) and N = 31 twenty-four month-old toddlers (14 female, mean age = 24.30 months, s.d. age = 0.35 months) were recruited from maternity wards or online in the Oxfordshire region of the United Kingdom. A further 4 participants (all twenty-four months) were excluded from analyses due to fussiness. The planned sample size was 70 – 75 participants, in roughly equal numbers. All participants were learning English as their first language.

Design

The experiment consisted of two parts: parental reports, and an automatic eye-tracking task. The parental report section utilised the Oxford Communicative Development Inventory (Oxford CDI, Hamilton, Plunkett, & Schafer, 2000). In addition, participants' caregivers were asked to fill out an additional report as to whether their child understood and produced each of 12 colour terms (*red*, *blue*, *green*, *yellow*, *black*, *white*, *orange*, *brown*, *purple*, *pink*, *grey*, & *aqua*).

The eye-tracking portion of the experiment was designed based on that of Johnson et al. (2011). In the eye-tracking task, each participant was randomly assigned to one of six stimuli lists, each of which consisted of several trial types. In each trial participants saw two different images, side-by-side, and were prompted to look at one. Trials were as follows:

4 **Target trials** were used to ensure that participants comprehended the target words. One of the objects on the screen was the object named.

4 **Unrelated Distractor trials** were used as a baseline for comparisons. Neither of the objects on the screen bore any relationship to the object named.

4 Related Distractor trials were used for the primary analysis, and these were either related semantically or by colour. One of the objects on the screen was related either by colour or semantically to the object named. Two of these trials used a food, and two used an animal as auditory stimulus. Two of these trials tested a semantic mediation (e.g. a food as auditory stimulus was matched with a food as visual stimulus), and two tested a colour mediation (e.g. a typically red object as auditory stimulus was matched with a red object as visual stimulus).

4 Colour Only trials operated the same way as the colour related trials above, but instead of hearing *"strawberry"* and seeing a red plate and a yellow t-shirt, on this occasion they saw a red plate and a yellow plate (see Johnson & Huettig, 2011). This manipulation gives greater power to analyse the colour related data, and also eliminated a bias due to the shape of the object, thus complementing the colour Related Distractor Trials.

10 Filler trials were used to maintain participant interest. As with the target trials, the object named was present on the screen. The only difference was that the filler trials did not contain any of the objects of interest of the study.

The full lists of trials and stimuli used in the study is listed in Table A1. Stimuli were counterbalanced so that in each list, each participant heard all 12 target stimuli: four as Target trials, to evaluate knowledge of the target objects, four as Related Distractor trials, and four as Colour Only Trials. The lists differed as to which stimuli the participants heard in each context, and the objects that were matched with them. Thus one participant may hear *"banana"* as an auditory stimulus, and see it matched with a picture of a banana in the target condition. Another may hear the word and see it matched with a yellow plate in the colour only condition. A third participant might hear *"banana"* and see it paired with a sandwich in a semantically related condition.

Stimuli

Auditory stimuli consisted of sentences encouraging participants to look at objects. In the filler trials, sentences consisted of the format, "where's the xxx?" All remaining trials were recorded in the format, "look at the xxx." In the target-present trials, the related distractor trials, and the colour only trials, there were 12 target words, 6 animal and 6 food, each of which can be characterised by a typical colour (e.g. *"strawberry"*). In the unrelated distractor trials, target words were objects that lacked a typical colour (e.g. *"hat"*). Ten additional words were chosen for use during filler trials. Each target word was chosen to be familiar to participants in both age groups, and which they were likely to know based on previous parental reports. All auditory stimuli were recorded by a native female speaker of Souther British English (SBE).

Visual stimuli consisted of high-resolution images of objects, manipulated so that each took up roughly the same amount of space on the screen. Where necessary, images were recoloured using the GNU Image Manipulation Program. All images that were chosen for colour only trials or related distractor trials were manipulated to be very typical examples of the colour category, in order to avoid ambiguity.

Procedure

Participants' caregivers were asked to fill out the Oxford CDI and additional parental report on colour terms (for more information see Forbes & Plunkett, 2018) prior to arriving at the lab, or on their arrival. Experimental sessions began with a short warm-up and play phase to allow participants to feel comfortable in the laboratory surroundings, during which time written consent was obtained from the caregiver. Once the participant had acclimatised to the surroundings, the eye-tracking experiment would begin. Participants were seated on the caregivers lap, at approximately 75cm from the screen. A nine-point calibration sequence was performed until at least seven of the nine points were calibrated successfully.

In each trial (see Figure 1), participants first saw an attractive attention-getter for two seconds, before the main trial began. The beginning of the trial was marked by the appearance of two images on the screen, one on the left and one on the right. Trials each lasted seven seconds, with the target word onset occurring two seconds into the trials. All trials were presented in a randomised order, and counterbalanced so that each participant only heard each target word once.

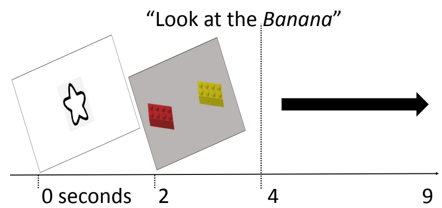

Figure 1. Time-line in seconds of eye-tracking trials: this is a typical Colour Only trial, where the intended target would be the yellow brick.

Analysis

Participants' looking was recorded using a Tobii eye tracker sampling at 120Hz. Trial automation and gaze processing were completed with custom Matlab code. Data was then analysed using the R package eyetrackingR (Dink & Ferguson, 2015) and lme4 (Bates et al., 2017). Looking to the target was determined by whether or not an toddler was deemed to have fixated on the target, with a fixation defined as a stable gaze in one location for upwards of 100ms (e.g. Chow, Davies, Fuentes, & Plunkett, 2016). Data was cleaned such that trials wherein a participant did not fixate one of the images for more than 60% of the trial duration were removed, in order to reduce noise. Data was only included for a trial if the caregiver had marked that the child comprehended the target word in the auditory stimulus (removing 225 trials in total).

Results

Overall Results

Overall average looking proportions for all participants for the main trial types can be viewed in Figure 2. The overall proportions in the Target trials remained consistently above chance (0.5) after the onset of the target word, suggesting that participants on average correctly understood the target word, and looked primarily at the corresponding object. The Target trials looking starts above chance, due largely to the visual attractiveness of the animal targets.

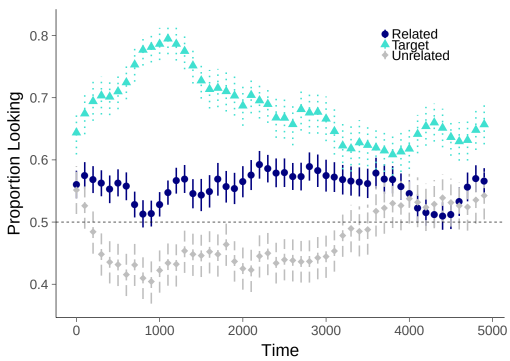

Figure 2. Overall results, collapsing over age, from target word onset. Related trials include colour related, semantically related, and colour only trials. The dotted line indicates chance looking at 50%. Error-bars represent standard errors of the mean. Unrelated trials are measuring the proportion of looks to the right.

In the Unrelated trials, looking was largely around chance, with some side bias, due in part to the fact that images were not left-right counterbalanced in this condition.

The Related trials in Figure 2 pool the Semantically Related trials, the Colour Related trials, and the Colour Only trials. Overall attention to the objects in the related trials, separated by age group can seen in Table 1. In these trials the proportion of looking to the related image is only slightly above chance. The following analyses examine the results of these trials in more depth. All proportions of looking to the related image in this study take the proportions of looks to the Related image, divided by the total proportion of looking to either image:

$$Prop = \frac{looks_{target}}{looks_{target} + looks_{distractor}}$$

Table 1
Proportional attention paid to the screen in the main (colour and semantic) trials by age group.

Age	Mean Attention	SD
19	0.900	0.099
24	0.886	0.123

Looking in semantic trials is consistently above chance in both age groups, in concordance with Johnson et al. (2011). Collapsing over time in each trial, participants looked consistently more to the related distractor in the Semantic condition than in the Colour conditions (Welch two sample t-test $t(86.633) = -3.291$, $p = 0.001$, $95\% CI = -0.204 - -0.050$). Looking to the related distractor in the Colour condition was at chance (One sample t-test $t(64) = 0.813$, $p = 0.419$, $95\% CI = 0.473 - 0.564$), while the Semantic (One sample t-test $t(44) = 4.673$, $p < 0.001$, $95\% CI = 0.583 - 0.708$) condition was above chance. The looking proportions in the semantic condition can be seen in Figure 3. A post-hoc comparison revealed no effect of age in the looking proportions in the Semantic condition (Welch two sample t-test $t(35.539) = 0.492$, $p = 0.626$, $95\% CI = -0.100 - 0.164$).

Colour results by age

In these analyses, only the Colour Related, and Colour Only trials are analysed. Colour trials combine Colour Related trials and Colour Only trials, for a total of 6 trials per participant, in order to increase statistical power. In the time window of interest (0 to 3000ms), no strong evidence was found for a difference in proportion of looks to the target in the Colour Related trials and the Colour Only trials ($t(95.597) = -0.419$, $p = 0.677$, $95\% CI = -0.010 - 0.065$), which allows combining the two (Figure 4).

The proportion of looking to the colour-related image was modelled with a hierarchical multilevel bino-

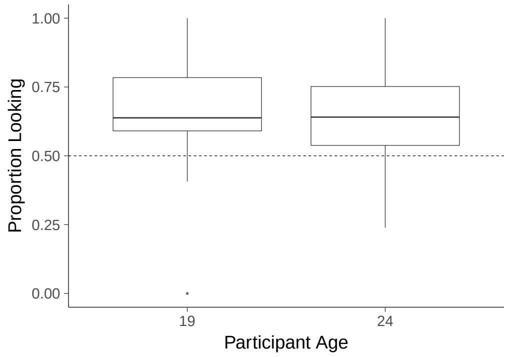

Figure 3. Looking proportions to the target in the Semantic condition.

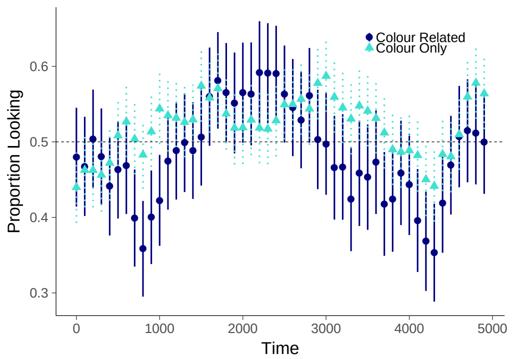

Figure 4. Looking proportions to the target over time in the colour conditions.

mial model, which operates by using the binary outcome of fixation in the target area versus fixation in the distractor area. The use of this statistical method, as opposed to collapsing over time, allows a thorough examination of effects as they appear over time, as well as the contributing variables. These results were modelled with orthogonal quartic polynomials of time (elapsed after the target word onset during each trial, Mirman, 2014), and included the main effects of age group (19 or 24 months), as well as all interaction effects between the polynomials and age group. The intercept term and the linear polynomial were allowed to vary by participant, in order to maximize model fit while not over-fitting the data. All fixed effects were difference-coded, and added in to the model with the optimal random effect structure individually.

The model coefficients (Table 2) suggest that there was strong evidence for an effect of age, and of an interaction with the linear, quadratic, cubic, and quartic polynomial terms. These results suggest there was a substantial difference between both the overall amount that each age group looked to the colour-related distractor, as well as a difference in the looking patterns of each age group. The model fit to the raw data points can be viewed in the top frame of Figure 5.

Table 2
Model coefficients of age-based model. "ot" refers to the orthogonal time terms, such that ot1 refers to the linear term, ot2 the quadratic, etc.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.90	0.53	1.69	0.091
ot1	4.85	4.36	1.11	0.266
ot2	-0.03	2.13	-0.01	0.988
ot3	0.09	1.16	0.08	0.939
ot4	0.21	0.38	0.55	0.581
Age	-4.43	0.99	-4.46	<0.001
ot1:Age	-46.22	5.87	-7.88	<0.001
ot2:Age	-37.94	3.34	-11.37	<0.001
ot3:Age	-17.56	1.82	-9.66	<0.001
ot4:Age	-3.99	0.60	-6.62	<0.001

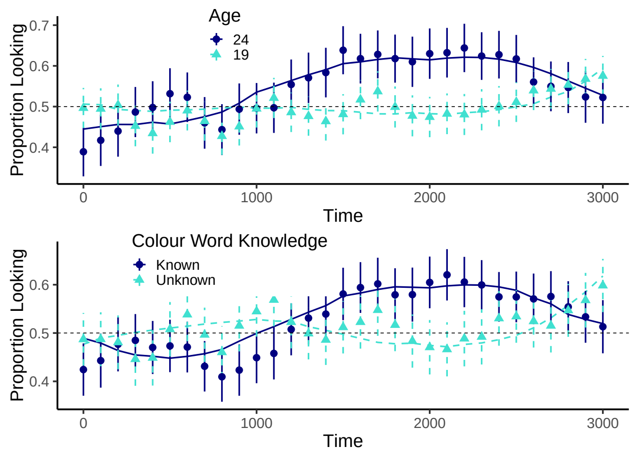

Figure 5. Colour trials vs semantic trials, fitted with a model by age in the top frame, and by knowledge of the relevant colour word, in the bottom frame.

19-month old participants look to the related picture only at chance for the first three seconds following target word onset, suggesting that they are not influenced by the label to look at the colour-related distractor. By contrast, the 24-month old participants begin shifting their gaze toward the colour-related picture after approximately 1000ms, showing a strong preference for the object of the same colour as the labelled object in the second and third seconds of the trial following target word onset.

The results of the model suggest that while 24-month old toddlers tend to fixate a colour-matched object when hearing a target word, 19-month old toddlers do not. However, based on results of previous studies (Johnson et al., 2011), participants should look to the colour-related distractor regardless of their knowledge of the colour word. Since colour word knowledge will, by necessity, improve with age (Forbes & Plunkett, 2018), examining the difference by age does not completely disentangle colour word knowledge from other age-related factors that may mediate attentional distribution.

Colour results by colour word knowledge

In this analysis, the results were analysed in the same manner as in the model by age above, but with one critical difference: the variable of age was replaced by the variable of whether or not the participant was deemed to comprehend the relevant colour term (i.e. "*red*" in the case of "*strawberry*", or "*yellow*" in the case of "*banana*"), based on the parental report.

The model coefficients (Table 3) show strong evidence for an effect of participants' comprehension of the relevant colour term, as well as strong evidence for that knowledge interacting with each of the orthogonal time terms. There was also evidence of effects of each of the orthogonal time terms. This result highlights that participants look differing amounts based on whether they know the colour word, and their pattern of looking is also different.

This model showed the same patterns of looking in the colour-word knowledge model as in the age model (the bottom panel of Figure 5). The participants who did not understand the colour word relevant to the target word show looking to the target largely at chance in fixation choices throughout the first three seconds of the trial, with some late looking at the colour-related distractor around the three-second mark. The participants who understand the relevant colour term look to the target in exactly the same way as the 24-month olds do, with a peak in looking during the 1000-2000ms time window. The match between the two models suggests that it may be colour word knowledge, rather than another, separate factor which is contributing to this effect.

Finally, the knowledge-based model (AIC 53428) was compared to the age-based model (AIC 53510) on the bases of the Akaike Information Criterion (AIC Akaike, 1998), with the lower AIC suggesting the knowledge based model fits the raw gaze fixation data better than the age-based model. This analysis further suggests that participants' looking to the colour-related object was driven more by their knowledge of the colour term than by another property relating to their age.

Table 3
Coefficients of knowledge-based model. "ot" refers to the orthogonal time terms, such that ot1 refers to the linear term, ot2 the quadratic, etc.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	1.51	0.52	2.88	0.004
ot1	10.88	4.29	2.54	0.011
ot2	4.94	2.12	2.33	0.020
ot3	2.43	1.15	2.11	0.035
ot4	0.77	0.37	2.06	0.039
Knowledge	-4.05	0.44	-9.30	<0.001
ot1:Knowledge	-39.15	4.26	-9.19	<0.001
ot2:Knowledge	-30.61	3.44	-8.90	<0.001
ot3:Knowledge	-13.73	1.87	-7.34	<0.001
ot4:Knowledge	-1.97	0.62	-3.19	0.001

Results at 19 Months

In order to demonstrate that looking to the target was an effect of knowing the colour word, rather than age, a subsequent analysis was done only on a subset of participants. Since a large majority of the 24-month olds knew the relevant colour words whereas a substantial number of 19-month olds did not[2], we evaluated the patterns of looking for just the 19-month olds, comparing those reported to know the relevant colour word with those who did not. In this analysis of the 19 month-old participants, and as with the previous analyses, only the Colour trials were included. The model was fit in the same way as in the previous analysis, by knowledge of the relevant colour word. The only difference was that only cubic polynomial time terms were used to fit this model, as a visualisation of the shape of the data indicated that there was no need for a quartic component (see Mirman, 2014).

The model coefficients (Table 4) demonstrate strong evidence toward an effect of the linear and quadratic time terms, as well as an effect of knowing the colour word, and interactions between that knowledge and each of the time terms. Nineteen month old participants show a similar pattern of looking as the overall group (Figure 6), if they know the relevant colour word: 19-month olds look systematically at the colour related distractor, in a similar time window as the overall group. If the participants do not know the colour word at nineteen months, they show no pattern of systematic looking during the same time window as that of the overall data.

[2]Unsurprisingly, there was very strong evidence that Age (19 vs. 24 months) and Colour Knowledge (Known vs. Unknown) were associated ($\chi^2(1) = 7.532$, $p = 0.006$).

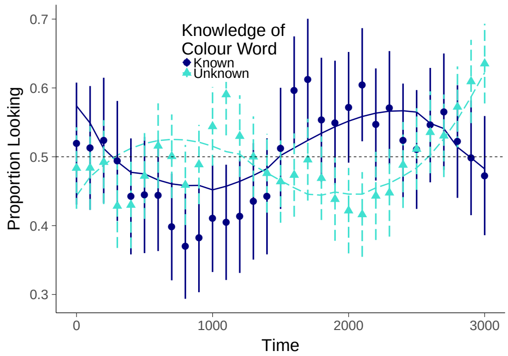

Figure 6. Model fit on nineteen month-old participants, by colour word knowledge

Table 4

Model coefficients of knowledge-based model run only with 19 month-olds. "ot" refers to the orthogonal time terms, such that ot1 refers to the linear term, ot2 the quadratic, etc.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.93	0.33	2.79	0.005
ot1	7.54	2.38	3.17	0.002
ot2	3.20	0.78	4.07	<0.001
ot3	0.62	0.33	1.86	0.063
Knowledge	-2.88	0.23	-12.33	<0.001
ot1:Knowledge	-28.62	2.18	-13.13	<0.001
ot2:Knowledge	-21.71	1.56	-13.91	<0.001
ot3:Knowledge	-9.51	0.63	-15.18	<0.001

The Role of Total Vocabulary

Toddlers learn words rapidly as they age (Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998). Not only is there a strong association between the age of the participant and their knowledge of the relevant colour word, but also between their knowledge of the colour word and their knowledge of all other words. To confirm that their behaviour in this task is driven primarily by their knowledge of the relevant colour word and not their overall vocabulary size,[3] two models were fit to the 19 month-olds data: the first, identical to the 19 month-old knowledge-based model run previously; the second, also the same, but replacing knowledge of the relevant colour term with overall receptive vocabulary as a proportion of terms in the Oxford CDI. The lower AIC of the knowledge-based model (AIC 28177) compared to the CDI-based model (AIC 28348), suggests that the knowledge-based model fits the data better than the CDI-based model. Thus toddlers' behaviour in this task appears to be driven by their knowledge of the relevant colour term, rather than their overall receptive vocabulary.

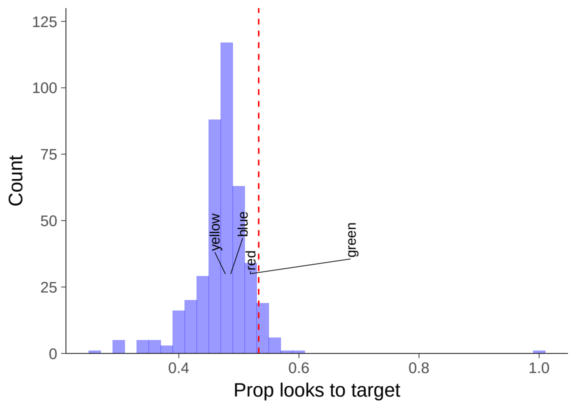

Figure 7. Proportions of looking to related distractor in the 1500 - 2500ms time bin when each of the words in the Oxford CDI is known. The dotted line indicates the proportion when the relevant colour word is known. The one word with a proportion of 1 occurred due to only one participant knowing that word. The proportions of the four colour words in the Oxford CDI are given for reference.

Finally, since knowing any one term increases the chance of understanding any other term, a final test was conducted to ensure that the results above were the result of knowing the relevant colour word, and not knowing just another, random word. Only fixations during the 1500 - 2500ms time window were examined. First, each of the 416 terms in the Oxford CDI were taken, then proportions of looks to the related distractor in that time window were calculated for when each of those terms were comprehended by the participants. Those proportions were compared to the proportions of looks to the related distractor when the relevant colour word was known, using a one sample t-test. In the target time window, looking to the related distractor given knowledge of any given word in the Oxford CDI (Figure 7) was less than the proportion when they knew the relevant colour word (One sample t-test $t(413) = -23.854$, $p < 0.001$, $95\%CI = 0.467 - 0.477$).

In a colour word mediated looking task, shifts in attention toward a colour related object are driven by whether the colour word is known to participants as reported by the child's parents, not by the participants' age, nor by their total vocabulary size, nor by their knowledge of another, random word.

[3]Participants who did not complete the Oxford CDI (10 participants) were removed from the subsequent analyses.

Discussion

In accordance with previous findings (Johnson & Huettig, 2011; Johnson et al., 2011), the present study has found that even young toddlers systematically attend to both semantic and colour related distractors when hearing an associated object label. Using a different test measure and population to the original study, the results of the present study challenges past results, however, finding that in a language-mediated attention task, the ability to systematically fixate on the colour related distractor when hearing the name of a typically coloured object is determined by whether the toddler understands the relevant colour word. This finding was also verified by examining a group of 19 month-olds, confirming that the effect was one of colour word knowledge, not just of age, nor of total vocabulary size. These findings support several possibilities regarding the role of colour words in mediating attention in a task such as the one described:

1. An associated colour word is activated upon hearing the name of an object that typically possesses that colour. Lexical activation of the associated colour word directs the listener's attention to objects that possess this colour. This explanation is an example of *label-mediated activation* described in the introduction.

2. Learning colour words enhances the perceptual or cognitive salience of those colours, leading to heightened attention to objects sharing those colours. This explanation is an example of *direct activation*.

We believe that both of these explanations, which need not be mutually exclusive, offer plausible accounts of the pattern of results reported in this experiment. For example, we know that semantically-related words in the toddler's mental lexicon rapidly priming each other, e.g., the word *dog* primes the word *cat*(Arias-Trejo & Plunkett, 2009, 2013; Styles & Plunkett, 2009). Although these studies report priming effects for words that are taxonomically and/or thematically related, it is not unreasonable to suppose that *property* words might also be activated by a related object word. Thus, hearing the word 'strawberry' may prime the word 'red' in the toddler's mental lexicon and direct attention to another red object. Picture priming tasks with toddlers (Mani & Plunkett, 2010; Mani et al., 2013) also point to the efficacy of internally-generated labels directing attention to related objects. These lexical-semantic networks are already in place by 18-months of age (Delle Luche, Durrant, Floccia, & Plunkett, 2014).

An alternative explanation for the behaviour exhibited in this experiment, is that the looking to the colour related distractor could be affected by a hidden moderator. In testing the idea that looking in these trials was moderated by general word learning, rather than by the associated colour word, we have gone some way to addressing this query. However, the possibility remains that another correlated aspect of behaviour, such as attentional capacity, could be driving looking behaviour. Attentional capacity may be correlated with colour word learning, and word learning in general, and thus difficult to disentangle from other possible explanations for behaviour in this task.

Toddlers in the present study systematically looked to the colour related distractor when hearing the label of a typically coloured object, but of note is the fact that they do so slower than their recognition of a named target. The peak looking in the colour trials occurs in the third one-second window after target label onset, almost 1000ms after the peak looking in the target present trials. This raises the possibility of cascaded effects (Huettig & McQueen, 2007), where perhaps colour effects occur after semantic and other effects, a result previously found by Mani et al. (2013).

Research into how colour words are learned has shown that colour categories change as a colour word is learned (Wagner et al., 2013, 2018). Initially, colour terms are over-extended. Toddlers divide the spectrum with the terms that are available to them, resulting in boundaries for each colour category that are excessively broad. As additional colour terms are learned, the existence of additional colour categories is highlighted, promoting language-specific categorisation of the colour spectrum. This is part of a general process by which toddlers develop linguistic colour categories on top of their pre-linguistic colour categories (Skelton, Catchpole, Abbott, & Franklin, 2017), to reach an adult-like understanding of colour words. This process varies greatly by language and by frequency of exposure to the colour words (Forbes & Plunkett, 2018). Again, it is not unreasonable to suppose that the fine-tuning of colour categories through exposure to language-specific labelling events highlights the salience of those colour categories, and facilitates the recognition of colour properties that are shared amongst objects. In the present study, toddlers need not necessarily activate the appropriate colour word in order to activate the colour concept, but their ability to match, from memory and abstraction, the colours, may be affected by their ongoing language-driven formation of these colour categories. Nineteen months marks the earliest stages of colour word learning in British English (Forbes & Plunkett, In Press; Wagner et al., 2018), and as such the shift that occurs in colour categories during this period may affect their performance in this task.

Even at the older age group, semantically-related distractors were more successful at guiding participant looking than colour-related distractors, a similar result to that found by (Johnson et al., 2011). This may reflect the "usefulness" of the semantic contextual information over the colour contextual information. A priming study by Mani et al. (2013) which put colour in direct competition with semantic information found that toddlers place a much higher informational value on semantic representations than colour representations, and thus look to the semantic target over the colour target.

In the current study, it was demonstrated that the proportion of looks to the related distractor was best predicted by whether the toddler knew that particular colour word. This was then contrasted to the null hypothesis that it could be equally well predicted by any other random word from the Oxford CDI, but the proportions for the relevant colour word generally remained higher, with few exceptions, despite the correlation between colour word learning and vocabulary growth. Figure 7 further demonstrates that the proportions for the four colour words in the Oxford CDI are also lower than that of the relevant colour word. It is, however, impossible to completely rule out the hypothesis that it is the toddlers general colour vocabulary comprehension, rather than their knowledge of that particular colour word, that guides their attention in this task. A toddler's early comprehension of colour words is often only partial (Wagner et al., 2014), and once a partial comprehension for the first colour word is learned, many others follow swiftly after (Mervis et al., 1995).

The present study differed from the original Johnson et al. (2011) study in several aspects, most crucially in the measure of how participants were judged to have comprehended the colour words used in the study. Johnson et al. used an eye-tracking task at the end of the experiment where participants saw smiley faces in each colour, and were prompted to look at one with a colour label. Eye-tracking tasks such as these are an effective measure of colour comprehension (Forbes & Plunkett, 2017, In Press), however the fact that they were at the end of the experiment could be a factor in the differing results between that study and the present study. Colour preferences can also be a factor in that kind of experiment (Forbes & Plunkett, In Press), which could also be an additional variable explaining the difference between the results of the two studies. Not many of the participants in the original Johnson et al. (2011) study were reported to be producing any colour terms at all, but as a partial comprehension of colour terms precedes production, this does not necessarily indicate a lack of comprehension, at least at a basic level. Determining at what level of colour word comprehension attention can be mediated in a task such as the one presented here, may be an area for further study.

Further studies into colour abstraction and memory at different ages may serve to determine further the plausibility of the direct activation and label-mediated accounts. For example, if attention is mediated via a colour label then we expect attention to be directed by a prototype that is a typical representation for that colour, for example a very typical green. In contrast, if attention is mediated directly by the mental representation of the object itself, of which the colour is one characteristic, then object-specific colour characteristics may be more influential in directing attention, e.g., frogs may be considered 'green' but not necessarily a prototypical green, and the green of the frog may be a better at directing attention than a prototypical green.

What are the implications of this study for other types of object property labels, such as those referring to texture, size and shape? We know that toddlers are able to generalise word meanings on the basis of such properties (Landau, Smith, & Jones, 1988; Jones & Smith, 2002). It is not clear that knowledge of labels for these properties is required for such generalisation to occur. However, a clear implication of the current study is that knowledge of property labels is likely to highlight attention to such properties in a language-mediated attention task, either through direct activation or indirect label-mediated activation. Research into the shape bias in early development has demonstrated that the that attention to object properties is mediated by the individual words that the toddler knows, and by the size of their vocabulary (Perry & Samuelson, 2011; Yee, Jones, & Smith, 2012). Thus the words learned do not have concrete definitions, but are dependent on the toddler's vocabulary structure and past experiences (Perry & Saffran, 2016). In the same way, the findings here highlight the importance of having learned colour words in attending to the property of colour.

The results of the present study suggest that in cognition about the features of objects, labels are essential mediators, even if they do not have a direct, top-down role in cognition. This is not to say that labels are necessary for the comprehension of a concept, but that the label may provide additional information about the category, acting as an additional feature of the category.

Thus there is a role for linguistic information, even if not a direct, Whorfian account. For the case of colour properties, we have demonstrated that there is an undeniable role for colour words in a language-mediated attention task. These words may achieve their effect either through implicit activation via word priming, or through highlighting the importance of colour in evaluating the similarity between objects. In either case, even the *unheard* word impacts attention in a visual search task.

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Table A1
Complete list of stimuli used during eye-tracking experiment

List	Trial Condition	Pictured Objects	Named Target
1	Target	Crocodile, Blue Ball	Crocodile
1	Target	Red Trousers, Elephant	Elephant
1	Target	Red Toothbrush, Cheese	Cheese
1	Target	Carrot, Green Bike	Carrot
1	Unrelated Distractor	Brown Dog, Black Shoe	House
1	Unrelated Distractor	Green Car, Red Apple	Table
1	Unrelated Distractor	Blue Helicopter, White Truck	Hat
1	Unrelated Distractor	Black Watch, Yellow Plane	Book
1	Related Distractor (SA)	White Plate, Fish	Pig
1	Related Distractor (CA)	Green Bowl, White T-Shirt	Sheep
1	Related Distractor (SF)	Sandwich, Green Sock	Chocolate
1	Related Distractor (CF)	Yellow Nappy, Purple Dress	Banana
1	Colour Only (COA)	Black Button, Brown Button	Monkey
1	Colour Only (COA)	Green Bib, Blue Bib	Frog
1	Colour Only (COF)	Red Zip, White Zip	Milk
1	Colour Only (COF)	Red Block, Yellow Block	Strawberry
1	Filler	Telephone, Hand	Telephone
1	Filler	Balloon, Doll	Doll
1	Filler	Tree, Fork	Tree
1	Filler	Train, Spoon	Train
1	Filler	Door, Cat	Door
1	Filler	Cat, Door	Cat
1	Filler	Train, Spoon	Spoon
1	Filler	Fork, Tree	Fork
1	Filler	Doll, Balloon	Balloon
1	Filler	Telephone, Hand	Hand
2	Target	Blue Ball, Crocodile	Crocodile
2	Target	Elephant, Red Trousers	Elephant
2	Target	Cheese, Red Toothbrush	Cheese
2	Target	Green Bike, Carrot	Carrot
2	Unrelated Distractor	White Truck, Blue Helicopter	Table
2	Unrelated Distractor	Yellow Plane, Red Apple	Hat
2	Unrelated Distractor	Black Shoe, White T-Shirt	House
2	Unrelated Distractor	Black Watch, Brown Dog	Book
2	Related Distractor (SA)	Purple Dress, Lion	Sheep
2	Related Distractor (CA)	Pink Mitten, Green Sock	Pig
2	Related Distractor (SF)	Blue Nappy, Green Apple	Banana
2	Related Distractor (CF)	Flower, Brown Bag	Chocolate
2	Colour Only (COA)	Green Zip, Black Zip	Frog
2	Colour Only (COA)	White Block, Brown Block	Monkey
2	Colour Only (COF)	Yellow Button, Red Button	Strawberry
2	Colour Only (COF)	White Bib, Blue Bib	Milk
2	Filler	Telephone, Hand	Telephone
2	Filler	Balloon, Doll	Doll
2	Filler	Tree, Fork	Tree
2	Filler	Train, Spoon	Train
2	Filler	Door, Cat	Door
2	Filler	Cat, Door	Cat

2	Filler	Train, Spoon	Spoon
2	Filler	Fork, Tree	Fork
2	Filler	Doll, Balloon	Balloon
2	Filler	Telephone, Hand	Hand
3	Target	Black Shoe, Pig	Pig
3	Target	Pink Mitten, Sheep	Sheep
3	Target	Green Sock, Chocolate	Chocolate
3	Target	Banana, White Truck	Banana
3	Unrelated Distractor	Green Bike, Blue Ball	Table
3	Unrelated Distractor	Yellow Plane, Red Toothbrush	Hat
3	Unrelated Distractor	Black Watch, Yellow Nappy	House
3	Unrelated Distractor	Red Apple, Purple Dress	Book
3	Related Distractor (SA)	Black Dog, Blue Cup	Monkey
3	Related Distractor (CA)	Brown Table, Green Bowl	Frog
3	Related Distractor (SF)	Sandwich, Pink Mitten	Milk
3	Related Distractor (CF)	Blue Trousers, Red Plate	Strawberry
3	Colour Only (COA)	Green Zip, Yellow Zip	Crocodile
3	Colour Only (COA)	Green Bib, Grey Bib	Elephant
3	Colour Only (COF)	Yellow Button, Blue Button	Cheese
3	Colour Only (COF)	Red Block, Orange Block	Carrot
3	Filler	Telephone, Hand	Telephone
3	Filler	Balloon, Doll	Doll
3	Filler	Tree, Fork	Tree
3	Filler	Train, Spoon	Train
3	Filler	Door, Cat	Door
3	Filler	Cat, Door	Cat
3	Filler	Train, Spoon	Spoon
3	Filler	Fork, Tree	Fork
3	Filler	Doll, Balloon	Balloon
3	Filler	Telephone, Hand	Hand
4	Target	Pig, Black Shoe	Pig
4	Target	Sheep, Pink Mitten	Sheep
4	Target	Chocolate, Green Sock	Chocolate
4	Target	White Truck, Banana	Banana
4	Unrelated Distractor	Black Watch, Red Toothbrush	Table
4	Unrelated Distractor	Yellow Nappy, Purple Dress	House
4	Unrelated Distractor	Blue Ball, Yellow Plane	Hat
4	Unrelated Distractor	Red Apple, Green Bike	Book
4	Related Distractor (SA)	Fish, Sandwich	Frog
4	Related Distractor (CA)	Green Bowl, Brown T-Shirt	Monkey
4	Related Distractor (SF)	Brown Table, Green Grapes	Strawberry
4	Related Distractor (CF)	Pink Mitten, White Chair	Milk
4	Colour Only (COA)	Grey Button, Black Button	Elephant
4	Colour Only (COA)	Green Block, Yellow Block	Crocodile
4	Colour Only (COF)	Orange Zip, White Zip	Carrot
4	Colour Only (COF)	Yellow Bib, Blue Bib	Cheese
4	Filler	Telephone, Hand	Telephone
4	Filler	Balloon, Doll	Doll
4	Filler	Tree, Fork	Tree
4	Filler	Train, Spoon	Train
4	Filler	Door, Cat	Door
4	Filler	Cat, Door	Cat

4	Filler	Train, Spoon	Spoon
4	Filler	Fork, Tree	Fork
4	Filler	Doll, Balloon	Balloon
4	Filler	Telephone, Hand	Hand
5	Target	Black Watch, Frog	Frog
5	Target	Blue Helicopter, Monkey	Monkey
5	Target	Strawberry, Brown Table	Strawberry
5	Target	Black T-Shirt, Milk	Milk
5	Unrelated Distractor	Yellow Plane, Red Toothbrush	Hat
5	Unrelated Distractor	Black Shoe, Green Sock	Table
5	Unrelated Distractor	Red Plate, Blue Trousers	House
5	Unrelated Distractor	Green Apple, Purple Dress	Book
5	Related Distractor (SA)	Lion, Blue Cup	Crocodile
5	Related Distractor (CA)	Green Bowl, White Truck	Elephant
5	Related Distractor (SF)	Red Chair, Cookie	Cheese
5	Related Distractor (CF)	Orange Dress, Brown Dog	Carrot
5	Colour Only (COA)	White Button, Red Button	Sheep
5	Colour Only (COA)	Green Bib, Pink Bib	Pig
5	Colour Only (COF)	Black Zip, Yellow Zip	Banana
5	Colour Only (COF)	Brown Block, Blue Block	Chocolate
5	Filler	Telephone, Hand	Telephone
5	Filler	Balloon, Doll	Doll
5	Filler	Tree, Fork	Tree
5	Filler	Train, Spoon	Train
5	Filler	Door, Cat	Door
5	Filler	Cat, Door	Cat
5	Filler	Train, Spoon	Spoon
5	Filler	Fork, Tree	Fork
5	Filler	Doll, Balloon	Balloon
5	Filler	Telephone, Hand	Hand
6	Target	Monkey, Blue Helicopter	Monkey
6	Target	Frog, Black Watch	Frog
6	Target	Milk, Black T-Shirt	Milk
6	Target	Brown Table, Strawberry	Strawberry
6	Unrelated Distractor	Yellow Plate, Blue Cup	Hat
6	Unrelated Distractor	Orange Dress, Green Sock	Table
6	Unrelated Distractor	Red Plate, Blue Ball	Book
6	Unrelated Distractor	Yellow Plane, Black Shoe	House
6	Related Distractor (SA)	Red Chair, Brown Dog	Elephant
6	Related Distractor (CA)	Pink Mitten, Green Bowl	Crocodile
6	Related Distractor (SF)	White Truck, Green Grapes	Carrot
6	Related Distractor (CF)	Yellow Nappy, Red Toothbrush	Cheese
6	Colour Only (COA)	Pink Zip, Blue Zip	Pig
6	Colour Only (COA)	White Bib, Green Bib	Sheep
6	Colour Only (COF)	White Button, Brown Button	Chocolate
6	Colour Only (COF)	Black Block, Yellow Block	Banana
6	Filler	Telephone, Hand	Telephone
6	Filler	Balloon, Doll	Doll
6	Filler	Tree, Fork	Tree
6	Filler	Train, Spoon	Train
6	Filler	Door, Cat	Door
6	Filler	Cat, Door	Cat

6	Filler	Train, Spoon	Spoon
6	Filler	Fork, Tree	Fork
6	Filler	Doll, Balloon	Balloon
6	Filler	Telephone, Hand	Hand