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Learning to Explore the World through its Statistics:
Infants' Visual Search in the A-not-B task

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Abstract

In searching for hidden objects, infants younger than 12 months frequently commit "A-not-B errors," in which they successfully search for an object in one location (A) and then fail to search for it when it is conspicuously hidden in a new location (B). Why do they fail to make the switch and perseverate at the first location? Although these errors have often been attributed to cognitive and conceptual limitations, we suggest that the answer is far more basic: in order to search successfully, children must first learn to do so. In what follows, we present an error-driven learning account of "A-not-B" search which suggests that failing to make the switch is an essential part of learning the appropriate searching cues and contextual search strategies. We elaborate the findings of an eye-tracking experiment with 9 month-olds that behaviorally confirms the predictions of our learning model.

Keywords: error-driven learning; search; A-not-B; feedback

It is Monday morning. You haven't seen your car keys since Friday evening. Where do you look for them? In an ideal world, you will go straight to where you last saw them. As an adult, you will have learned from previous experience that keys are not (usually) assigned random locations, and that what best predicts a key's location is the conjunction of a given spot and that spot being the most recent place the keys were seen. In a less than ideal world, however, you may not remember where you last saw the keys; other memories might compete with your specific memories from Friday. Indeed, when you aren't precisely sure where you last saw the keys, you may check the hook where you usually keep them first, because you know that searching at a location where they keys are seen frequently can (on other days) be a successful search strategy.

This story illustrates the task a child faces in learning to find things in the world. A child must learn that some things are most likely found at the location they were *last* seen, while other things are most likely found they are most *often* seen (while it makes sense to look for keys in the last place you saw them, if you haven't seen your cat for a while, you would be best off looking in the most frequent place the cat is found), and that a successful search will involve weighing these considerations against what the child remembers about the last and most frequent locations of an object. From this perspective, "perseverative errors," in which a child searches for an object in a most frequent location rather than a most recent, can be seen as a misapplication of what in other circumstances might be a logical strategy.

Piaget (1954) first described what are often called "A-not-B errors" in infants, namely that 8- to 12-month infants will generally search successfully for an object in an initial location (A) and then fail to search for it when it is conspicuously hidden in a new location (B) instead, continuing to search at location A. Subsequent studies have confirmed that in actively searching for hidden objects, infants robustly commit this prototypical A-not-B error, ignoring the last location of an object when they reach for it (see Marcovitch & Zelazo, 1999 for a meta-analyses). In seeking explanations for this reaching behavior, accounts have tended to assume that infants' errors stem from problems associated with implementing a correct search, such as limited working memory and inhibitory control, or from weak memory traces for the object and hiding location (e.g. Baillargeon, Graber, Devos, & Black, 1990; Diamond, 1988; Diamond, Cruttenden, & Neiderman, 1994; Munakata, 1997; Thelen, Schöner, Scheier, & Smith, 2001).

In what follows, we take a slightly different approach to thinking about the prevalence of the perseverative searching behavior. Rather than assuming that a child "knows" how to search, all other things (object concepts, memory, etc.) being equal, we consider what might be expected when children are *learning how* to search. As noted above, in learning to find objects, children have to figure out which strategy is appropriate in a particular context.

We consider the question of how children learn to discriminate between possible object retrieval strategies in a given context within the framework provided by formal *learning theories* (e.g. Rescorla & Wagner, 1972), which view learning as a process of acquiring information about the relationships between salient events (*outcomes*) in the environment, and the cues that allow those outcomes to be predicted. From this perspective, children's learning to search is a process of trial and error, each iteration of which strengthens or weakens cues depending on how well they predict an outcome (termed *error-driven learning*). While from an adult perspective, children's "perseverative" search may be erroneous, we suggest that from an infant perspective, their behavior is rational in following the often accurate cue of where something has been found most frequently. In the approach of learning theories, A-not-B "errors" are an inevitable, and logical, step along the path to adult search expertise, as infants go through the process of learning which situational cues best predict an outcome.

Mastering Search

In considering perseveration as part of a logical learning strategy, it is interesting to note that it is also evident when infants learn other (novel) relationships between cues and outcomes, and not just in hiding events. Aguiar & Baillargeon (2000), showed that 7-month-old infants perseverated in pulling a towel that had previously had a toy on it, even when the toy was now visibly on a different towel, and Smith, Thelen, Titzer, & McLin (1999) found that directing infants' attention to lids in an A-not-B pattern drew reaching behavior similar to when objects were hidden. These examples suggest that the perseverative response has more to do with the process of learning where to direct an action than particular properties of the objects or hiding events themselves. Munakata (1997) found that perseveration was reduced if the experimenter waved lids at A, but then hid a toy at B, suggesting that infants learn about particular outcomes at particular locations, such that if a *different* outcome is observed at a new location, it is less influenced by prior evidence.

Thus, it appears that A-not-B errors are not only due to prior motor habit (given that infants can switch when a new object is hidden at the new location), or by infants having trouble conceptualizing objects or not being interested in them (given that they search successfully at the first location). Infants appear to "understand" the task, so *why* do they fail to search correctly after a switch in location?

As we noted above, successfully searching for an object involves weighing a number of cues to its likely location: its last location, its usual location, the independent mobility of the object, etc. If a child doesn't know how to weigh those items correctly in search, then in the early stages of learning within a particular context, cues learned when an object is hidden at location A and then reappears at A may suggest to the infant that location A is the most *likely* location a hidden object will reappear from. When the object is first hidden at location B, the infant will have no experience of objects reappearing at B, and given that the situational cues provided by an object being at A and an object hidden at B overlap, the infant's best guess ought to be that the object will reappear at A. Given only this information, a child thus *ought* to continue to search at location A when the object has first been hidden at location B.

Over time, if we assume that the child in the A-not-B task is capable of learning (e.g., Rescorla & Wagner, 1972), the error resulting from incorrect searches at location A during trials when the object is hidden and retrieved from location B will *weaken* the cues that continue to predict that an object will be at location A. At the same time, cues supporting the prediction that location B is the correct location will *strengthen*. Eventually, the cues predicting that the object will reappear at location B will have more support than those predicting that it will reappear at A, and the infant will slowly come expect the object at B.

Moreover, since the cues supporting the general "search at the most frequent location" response will generate error over time as hiding locations are switched, while conjunctive cues that support searching at the specific place an object was last seen will continue to be accurate, this process will gradually result in conjunctive cues (that favor the most recent location) over cues favoring search at the most frequent location. Thus, the infant will gradually learn to weigh search strategies within a context from the evidence of their success and failure, and will then come to resemble the adult strategies described above.

Further, although we have talked so far about children 'learning to search,' the evidence is that children do not initially appear to learn abstract, generalized "search." While 9-month-old infants succeed in Aguiar & Baillargeon's (2000) towel pulling task, they still fail the standard A-not-B task (Piaget, 1954), even though the tasks are structurally similar. Rather than learning abstract "search," it appears that children may instead learn search and retrieval strategies within particular contexts.

To formally illustrate how children might learn the appropriate search strategy in the A-not-B task, we simulated this process using the Rescorla-Wagner (1972) learning model. In the model the change in associative strength between a cue C_i and a relevant environmental event E_j given a learning trial n is defined to be:

$$\Delta V_{ij}^{n} = \boldsymbol{\alpha}_i \boldsymbol{\beta}_j \, (\boldsymbol{\lambda}_j - V_{total})$$

This rule specifies how the associative strength (V) between individual cues (C_i) and an event (E_j) changes as a result of discrete exposure trials, where n indexes the current trial (V_{total} is the sum of the associative strengths between all CSs present on the current trial and US_j). The individual saliency of cues can be denoted by a parameter α_i (where C_i $0 \leq \alpha_i \leq 1$), the rate at which cues are learned with respect to an event is determined by a learning rate parameter β_j (where $0 \leq \beta_j \leq 1$), and the maximum amount of associative strength that an event E_j can support is denoted by value λ_j, such that the *amount learned* by the set of cues on a given trial is the value of $\lambda_j - V_{total}$, modulated by β and α.

In simulating children learning about the two locations (A and B) of the A-not-B task, we assume that on each trial infants will search at the location that they most strongly associate with the object's reappearance, and that the outcome of each search, either finding the object or not, will be incorporated into task learning and affect later search behavior. To reflect the fact that infants will most likely spend longer looking towards the location at which they expect objects to reappear (keeping in mind that this may not match the location in which the object was hidden), the saliency of the unattended location was set lower than that rate for the attended location.[1] This allowed the model to reflect the likelihood that infants would learn less quickly about location B when they were still primarily attending to A. This meant that, as a consequence of their attending to A, infants were initially slow to learn about hiding events at B.

To initially examine the learning problem facing an infant, we simulated the learning of cues that represented each location, and the strength of association between those cues and the object. Figure 1 shows these associative strengths changing across the trials (first at location A, then at location B) of a typical A-not-B task. Initially the association for the object at location A increases as objects are being hidden there. The association with location A then decreases slowly when hiding events begin at location B, because the error associated with unsuccessful search at location A reduces the value of cues predicting location A. For cues associated with location only, the model predicts that if hiding were to be later switched back to location A, learning to search at A would again proceed slowly, given that B is now strongly associated with the object's location.

However, unlike this model, which predicts that an infant will simply search at the location most associated with an object, children *do* eventually succeed on the A-not-B task, switching back and forth with ease, suggesting they need to learn about the conjunction between a location and the most recent hiding event. To reflect this, we added conjunctive cues to the model. The changing associative strength of the conjunctive cues, along with those of the simple location cues discussed previously, is shown in Figure 1. During the initial hiding events at A, there is nothing to distinguish between the simple and conjunctive cues, because each predicts the correct outcome at location A. However, after the switch in locations, the associative strengths of the simple cues are weakened because they fail to predict the object location as well as the conjunctive cues.

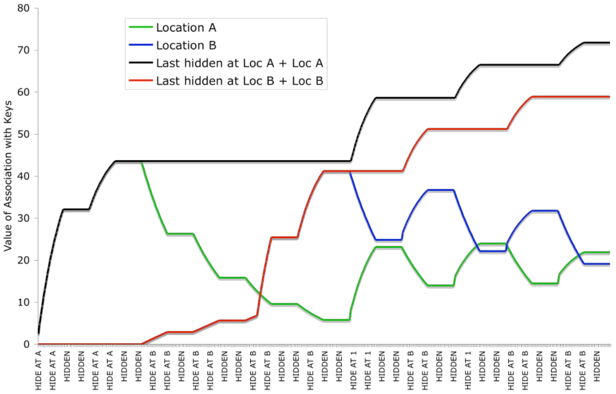

Figure 1: A Rescorla-Wagner model of cue competition between two cues representing location only, and two conjunctive cues representing last known location. The model shows associations with the hidden object across two trials at A, then four trials at B, then hiding events alternating between the two locations.

Learning and Visual search: Experiment 1

We suggested above that A-not-B errors are the result of a particular kind of search in a particular context, and that the relationships (and similarities) between the particular cues observed and the particular outcomes expected from those cues is a very important component in shaping children's early search behaviors. To examine our account of learning to search, we conducted a study of the visual search behavior of infants in an A-not-B paradigm using eye-tracking. Though the standard A-not-B task generally involves infants *reaching* for hidden physical objects, if our hypothesis about the need for infants to learn appropriate search strategies is correct, we would expect the same pattern of behavior to be apparent across modalities (see also Diamond, 1990; Hofstadter & Reznick, 1996; Bell & Adams, 1999). In addition, by measuring eye gaze across the duration of a specified search period in which both hiding locations were visible but neither was cued, we sought to acquire a continuous measure of children's attention to—and association between—each of the two regions and the objects shown to have been hidden there.

Methods

Participants 32 9-month-old infants successfully completed our testing procedure (range 8 months 17 days to 9 months 17 days, median 9 months 7 days; 16 males). An additional 13 infants failed to complete the experiment due to fussiness. Participants were recruited from a volunteer

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[1] α_i=0.05 for attended stimuli and 0.075 for unattended stimuli; the other parameter values for the simulations reported were: λ = 100% when the keys are visible at a given location or 0% when they are not visible at a given location and β_j=0.5.

pool, which reflects the properties of the community surrounding Stanford University.

Stimuli Stimuli were movies of colorful keys, accompanied by music. The keys were familiarized in center screen, and were then shown moving across the screen and disappearing into a bucket on one side of the screen. An identical bucket was present on the other side of the screen.

Following the disappearance of the keys, a pinwheel distracter appeared in the center of the screen for three seconds, then disappeared. For the following four seconds only the buckets were visible, while the music that accompanied the keys was played to encourage searching. After the four-second search period, the keys reappeared from the same bucket into which they had disappeared, before moving back towards center screen. The pinwheel animation then reappeared in center screen and remained until infants' attended to it, at which point the next trial began.

Procedure and design Participants sat on a caregiver's lap during testing, facing a 152cm projection screen, which was approximately 180cm from them. An Applied Science Laboratories (ASL) Model 504 corneal reflection eye tracking system collected eye movement data as infants were shown the stimulus displays. A computer script translated the gaze coordinates recorded by the system into gaze durations to regions of interest (ROI) defined around each of the hiding wells during the 4-second search period after each hiding event.

Infants were shown the key-hiding sequence six times: the keys were hidden twice in the bucket on one side of the screen, and then four times in the bucket on the other side of the screen, mimicking the sequence of a typical A-not-B task. Side of initial presentation was counterbalanced across participants.

Results and Discussion Looking-time data are presented as a difference in milliseconds between the amount of looking to the two ROIs, with positive values reflecting greater looking (bias) towards the A-side, and negative values reflecting greater looking (bias) towards the B side, calculated for each participant on each trial.

For data-analysis, the six trials were grouped into three pairs; the first two trials, in which the keys were shown hidden in location A, are labeled 'A trials'; the two subsequent trials, immediately following the switch to the new hiding location B are labeled 'early B trials'; and the last two trials in location B are labeled 'later B trials.' Because not all of the infant participants provided clean data from all six trials, pairing the trial data in this way allowed some missing cells to be filled in. Data was averaged for both trials if available, but if only one trial of the pair had clean data, then this trial was used.

Although the display shown to the infants was intended to mimic the manual A-not-B search task in presentation, the presentation could not be infant-controlled in the same way that manual studies can. In a manual search task, the toys can continue to be hidden at location A until the infant has reached a success criterion for searching at that location, ensuring that the infant has been attending to, and learning about, the hiding events; however, in the current visual search task, we were unable to employ such a criterion accurately in real time. Therefore, the presentation of hiding events continued without any performance-based contingency. Because our visual search task did *not* require success at location A prior to the switch in hiding to location B, we expected that there might be individual differences among the participants in extent of learning about location A, and that this difference might affect later search behavior. Consistent with the design of our model, we would not expect children to learn about hiding events that occurred at a location to which they were not attending.

We considered two possible measures of how much children learned about hiding events at location A. One that is predicted by the model is that infants who attend more to the actual hiding event, as the keys move towards the location in which is will be hidden, learn more about it. However, infants are capable of deploying covert attention, such that gaze does not necessarily imply attention (e.g. Johnson, M.H., Posner, M. & Rothbart, M.K., 1994). Therefore, we decided to use infants' looking behavior during the search period of hiding events at location A as evidence for how much they learned about those events. Following a hiding event at location A, an infant who looks a lot at the ROI for location A, and little at the ROI at location B, demonstrates a greater expectation for the object to be at (and reappear from) location A – the infant has learned something about what to expect about hiding events in the context! As might be expected, there is a correlation in the trials at location A between how much infants attend to the object as it moves towards a hiding location, and how much they look at location A during the search period (r=.456, p=.005), but in terms of making predictions about later search expectations, the actual extent of learning demonstrated during trials at location A seems more directly relevant as a measure, which is why we have chosen to focus on that.

Analysis confirmed that infants in the study varied in how much they looked towards location A during the search period of A trials, with 17 infants who (accurately) looked more at location A and another group of 15 infants who looked more at location B during that search period. An ANOVA comparing the searching patterns across the study between these two groups of infants (who searched differently during A trials) revealed the anticipated difference in the patterns of infants' looking across the study, $F(2,90)=34.597$, $p<.001$. Accordingly, the children were separated for remaining analyses: an 'attenders' group of children who looked more to A during the initial search trials, and a ‘non-attenders’ group who looked more to B during the initial search trials even though the keys were hidden at location A.

A further omnibus ANOVA, including attending status as a variable, revealed an overall ‘side’ x ‘time’ interaction, $F(1,92)=2.622$, p=.022, and a ‘side’ x ‘attending status’ interaction, $F(1,92)=5.435$, p<.001 (Figure 2). These results revealed an overall change in where the infants were looking during the search period across trials, and that this change was driven by the attenders, who searched first at location A and then changed their locus of search over time, as more hiding events occurred at location B. Unsurprisingly, the non-attenders did not change their searching behavior throughout the study.

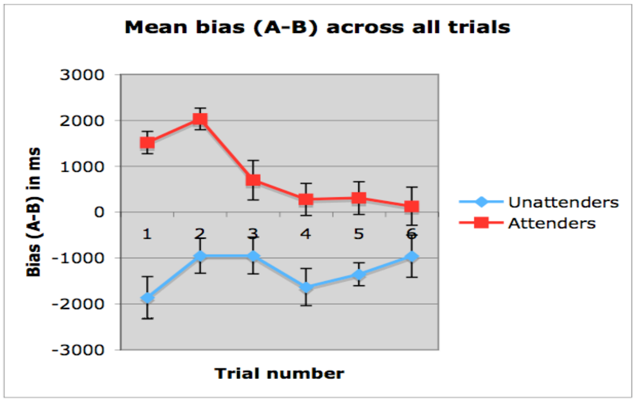

Figure 2: A plot of the difference in looking time to locations A and B across the visual search A-not-B task, (with the first two trials at location A and the remaining at location B) for each of the two groups (those who searched more at location A during the first two trials, attenders, and those who did not, non-attenders.

An analysis of the visual search of the attenders revealed a change in looking bias across the trials, with decreasing looking to location A, $F(1,49)=14.057$, p<.001. Despite this trend however, there was still a main effect of side in the study, $F(1,49)=29.468$, p<.001, with significantly more looking to A (M=2038 ms) than B (M=1192 ms), $t(1,50)=4.611$, p<.001, even there are twice as many hiding events at B than at A over the course of the experiment. This overall greater searching at location A within the attending group is noteworthy because it demonstrates the same perseverative trend seen in the typical A-not-B task with manual search. Along with the overall perseverative trend, however, the data are also consistent with the learning model presented. Specifically, children’s searching at the formerly correct location gradually lessens as the cues that predict that location are weakened following hiding events in a new location, and the rate of learning to search the alternative location is also slowed until attention shifts away from the initial location. Individual differences among the attenders elucidate this learning, with a regression showing that the extent of the searching bias A events “predicted” the extent of bias on early B-trials, p=.018, a relationship that was not significant for non-attenders.

The non-attenders, who did not learn about location A or the hiding events that occurred there, were not expected to behave in the same way as the attenders. While these non-attenders showed a main effect of side, $F(1,42)=10.979$, p=.002, this resulted from more overall looking to location B, $t(1,43)=7.282$, p<.001. More distinctly from the attenders, the non-attending infants did not change their looking bias over the course of the trials in different locations, $F(1,42)=.378$, ns. Since the non-attenders failed to notice the hiding events at A, there was no reason that they should later begin to search there. The fact that the non-attenders do not change their bias over time suggests that changes in search do not result simply from regression to the mean (a possible concern, because groups were split based on early search behavior), but reflect different patterns of learning over time in the two groups.

General Discussion

Children who initially learned about an object hidden at one location continued to search visually at that location even after the object was hidden elsewhere, but then showed a gradual shift in their search behavior away from the initial location and towards the new location. This pattern of data is consistent with the idea that learning is a function of experience and the expectations that experience produces (Rescorla & Wagner, 1972; Ramscar, Yarlett, Dye, Denny, Thorpe, in press; Ramscar & Dye, 2009) and suggests that when infants initially learn that objects will appear from A, they will “perseverate” in that response before gradually learning to predict the objects’ appearance at B. The correlation between the attenders’ bias during A trials and the early B trials, but *not* the later B trials, also supports the idea that the initial bias towards A must be unlearned, and that this will happen only as more hiding / appearance events are shown at location B (see also Diedrich, Thelen, Smith, & Corbetta, 2000). This gradual change in looking preference over time supports our hypothesis that search is something children have to learn, and that success or failure at different kinds of search is, to a degree, a matter of contextual experience.

Our results further suggest that infants given the same exposure to a particular hiding location may actually learn differently about it, in part because of the degree to which they attend to training. This variability in attending might not be evident in a reaching paradigm. For example, the results of a recent A-not-B study by Topal, Gergely, Miklosi, Erohegyi & Csibra (2008) are consistent with the idea that the degree to which children attend to hiding events at location A will impact the degree to which they perseverate in search to that location rather than a new hiding location. In their study, Topal et al. found that infants who were directed to hiding events with the highest level of engagement (both words and gestures) later showed the greatest perseveration to location A, while a group who saw only gestures was more likely to switch successfully to searching at location B. Although the groups had similar rates of searching at location A, that does not necessarily imply equal attention to or learning about hiding events in that location, because any attention drawn to location A should make a reach there more likely than to another location, given the forced-choice single measure outcome. A more continuous measure of attending or learning during trials at location A, such as eye tracking, could have confirmed whether this later difference in perseveration was because attention was actually increased to location A when the experimenter verbally engaged the infants, thereby increasing their learning about that location, and therefore increasing the time it took them to unlearn their response to location A, therefore leading to the observed greater perseveration to location A after the change in hiding location.

While there is much to explain with regards to the development of children's ability to search—and not least how the learning of conjunctive cues over extended trials might impact performance on the A-not-B task—we believe that there is insight to be gained from seeing infants' behavior in the A-not-B task in terms of *learning* to search, and the patterns of behavior that accompany such learning, rather than as a failure to search correctly. Not only does this approach offer an answer to the often puzzling search behavior of children, but we believe that the combination of eye-tracking and computational modeling methods used in the current study provide a useful formal framework for addressing these questions.

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