Toddlers search longer when there is more information to be gained

Azzurra Ruggeri*

Max Planck Research Group iSearch, Max Planck Institute for Human Development and School of Education, Technical University, Munich

Madeline Pelz

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

Alison Gopnik

Department of Psychology, University of California, Berkeley

Eric Schulz

Max Planck Research Group Computational Principles of Intelligence, Max Planck Institute for Biological Cybernetics

Author Note

*Correspondence should be addressed to Azzurra Ruggeri, Max Planck Institute for Human Development, Lentzeallee, 94, 14195 Berlin, Germany. Email: ruggeri@mpib-berlin.mpg.de

Abstract

One of the greatest challenges for artificial intelligence is how to behave adaptively in scenarios with uncertain or no rewards. One—and perhaps the only—way to approach such complex learning problems is to build simple algorithms that grow into sophisticated adaptive agents, just like children do. But what drives children to explore and learn when external rewards are absent? Across three studies, we tested whether information gain itself acts as an internal reward and motivates children's actions. We measured 24- to 56-month-olds' persistence in a game where they had to search for an object (animal or toy), which they never find, hidden behind a series of doors, manipulating the degree of uncertainty about *which specific object* was hidden. We found that children were more persistent in their search when there was higher uncertainty, and therefore more information to be gained with each action, highlighting the importance of research on artificial intelligence to invest in curiosity-driven algorithms.

Keywords: Active Learning, Information Gain, Developmental Psychology, Hypothesis Testing

Toddlers search longer when there is more information to be gained

Introduction

One of the greatest challenges for artificial intelligence is how agents can be designed to behave adaptively when there are uncertain, sparse or no rewards. Psychologists, computer scientists and roboticists have been keen to point out that one–and perhaps the only–way to approach such complex learning problems is to build simple algorithms that grow into sophisticated adaptive agents, similar to how children grow into adults. In particular, they suggest that, in such uncertain and dynamic scenarios, "curiosity-based" systems may do better than standard reinforcement learning methods (Pathak, Agrawal, Efros, & Darrell, 2017; Schmidhuber, 2010). Curiosity-based systems have in common the idea that quantitative increases in information gain are themselves rewarding and motivate actions, and are often explicitly inspired by the curiosity-based exploration of young children (Loewenstein, 1994). Even though it does seem crystal clear that young children are indeed curious and that this contributes to their impressive learning abilities (Alvarez & Booth, 2014), there has been no work to date investigating what motivates children to explore and learn in the absence of rewards.

Previous research has shown that, already by 11 months of age, infants prefer to explore surprising events (Stahl & Feigenson, 2015). This attentional capture can be characterized in terms of information gain (Kidd, Piantadosi, & Aslin, 2012), with infants showing the most attention to situations of intermediate visual complexity, supposedly to avoid wasting cognitive resources trying to process overly simple or overly complex events (Schmidhuber, 2010). Along these lines, a growing body of work has shown that children are more likely to explore when presented with confounded (L. E. Schulz & Bonawitz, 2007) or unexpected evidence (Bonawitz, van Schijndel, Friel, & Schulz, 2012), that they seek out uncertainty reduction more eagerly than adults (Meder, Wu, Schulz, & Ruggeri, 2020; E. Schulz, Wu, Ruggeri, & Meder, 2019) and are sensitive to the potential information gain of different actions (Jirout & Klahr, 2012; Ruggeri, Sim, & Xu, 2017; Ruggeri, Swaboda, Sim, & Gopnik, 2019).

However, although these results robustly indicate that children are meaningful and efficient explorers, they do not address the question of whether and to what extent the opportunity to gain information can systematically motivate young children's exploratory actions. Classic work in reinforcement learning shows that agents are more likely to act and act more persistently when pursuing greater rewards. Will preschoolers be more persistent in situations where there is more *information* at stake? Can expected information gain alone serve as an intrinsic reward, strong enough to drive exploration and learning? In the present studies, we measured how long toddlers and preschoolers, aged 2 to 4 years old, were willing to keep searching for something they never found. Children were told that they had to find an object (animal or toy) hiding behind one of a virtually infinite series of doors, sequentially presented on a screen (see Fig. 1). Across three studies, we manipulated the degree of uncertainty as to which specific object they were searching for, and measured the effects on children's search persistence.

In Study 1, we compared a condition where children were told which animal they were looking for (*1-animal* condition; e.g., find Sam, the lion) to a condition where they did not know which of eight possible animals was hiding (*8-animals* condition; i.e., find Sam, which could be a lion, an elephant, a hippo, a zebra, a crocodile, a bird, a turtle, or a whale, see Fig. 1). This subtle difference in the task instructions was enough to crucially impact the information gain (IG) of the same action (i.e., opening a door) across the different conditions. Indeed, intuitively, in the 8-animals condition, compared to the 1-animal condition, opening a door offered the opportunity to discover not only the location of the hidden animal, but also its identity. Formally, the information gained about the animal when opening one door in the 1-animal condition was IG=$-\log(1) = 0$, whereas in the 8-animals condition it was IG=$-\log(1/8) = 3$. In Study 2, we replicated and extended the results of Study 1, testing an independent sample of 2- to 4-year-olds on an even more subtle manipulation: Instead of contrasting a certain (1-animal) against an uncertain condition (8-animals), we varied the *degree* of uncertainty between conditions, comparing the same 8-animals condition from Study 1 with a 2-animals condition, where children did not know which of *two* possible animals was hiding (IG=$-\log(1/2) = 1$; see Fig. 1). In this sense, children in this condition still gained some additional information about the animal's identity upon searching, but to a lesser extent than in the 8-animals condition. In Study 3, we replicated and extended our investigation further by presenting an independent sample of 3- to 4-year-olds with the 1-animal and the 8-animals condition from Study 1, this time in a within-subjects design (order counterbalanced). This manipulation was crucial to capture to what extent the effects observed in Study 1 and 2 are stable and reliable at the individual level.

Study 1

Methods

Participants. We recruited 49 young children (range: 24 to 52 months, 26 female, $M_{\text{age}} = 38.06$; SD=7.77) from preschools and museums in the San Francisco Bay Area. Sample size in all studies was determined by conducting an a-priori power calculation based on the planned t-test comparison of number of doors opened in the two conditions (Cohen's d = 0.8, 80% power). Nine additional participants were excluded because they were distracted (n=4), could not operate the tablet (n=1), parental intervention (n=2), technical difficulties (n=1) or because the child did not understand English (n=1). Informed consent was obtained from the parents of all participating children. Ethics approval for Study 1 was obtained by the ethical review board of the University of California, Berkeley (protocol: CPHS#:2010-01-631).

Design and Materials. In this game, children were told to look for Sam, i.e., an animal hidden behind one of the doors. The experiment used a between-subjects design, where participants were assigned to either the 1-animal or the 8-animals condition. In the 1-animal condition, they were told which specific animal Sam was, randomly assigned for each child to be either a lion, an elephant, a hippo, a zebra, a crocodile, a bird, a turtle, or a whale. In the 8-animals condition, children were told that Sam could have been one of the eight animals, but were not told which one. The task was presented on a tablet, which presented a virtually infinite series of closed doors, displayed one at the time. After touching a door on the screen, it would open to reveal what was behind it. Afterwards, the next closed door would be displayed. The procedure and stimuli of Study 1 are illustrated in Fig. 1.

Crucially, in both conditions, the animal would never appear, i.e. there was nothing behind any of the doors. The session was ended when children gave up searching (e.g., left the table; see below) or if they had not given up searching after 4 minutes. At the end of the session, the experimenter encouraged children to open one more door, at which point they would actually find Sam.

Results

For all studies, we report both frequentist and Bayesian tests. Frequentist tests are presented alongside their effect sizes, i.e. Cohen's *d*. Bayesian statistics are expressed as Bayes factors (*BF*s), quantifying the likelihood of the data under the alternative compared to the null hypothesis. We apply Bayesian t-test for comparing independent groups, using a Jeffreys-Zellner-Siow prior with its scale set to $\sqrt{2}/2$. We perform Bayesian linear regression with a normal prior on the weights $\hat{\beta} \sim \mathcal{N}(0, 100)$.

We examined three indicators of children's persistence: the number of doors they opened before they stopped searching, the latency from the start of the experiment to the first time they showed signs of giving up the search (i.e., leaving their chair, looking away or not opening the currently presented door for longer than 10 seconds, talking to their caregiver, verbally expressing their frustration for not having found Sam just yet), and the proportion of children who kept opening doors until the predetermined time limit of 4 minutes. All measures converged in showing that children were more persistent in their search when the information gain of their actions was higher.

In particular, we found that children in the 8-animals condition, compared to children in the 1-animal condition, opened more doors on average (24.83 vs. 16.16 doors; Student's $t(47) = 3.43$, $p = .001$, Cohen's $d = 0.98$, Bayes Factor $BF = 50.8$) and searched for a longer time (133.22 vs. 91.31 seconds; $t(47) = 3.46$, $p < .001$, $d = 0.99$, $BF = 55.1$), as can be seen in Fig. 2, top and mid row of the left panel. Moreover, whereas only 7 out of 24 children reached the time limit in the 1-animal condition, 20 out of 25 did so in the 8-animals condition, see Fig. 2, bottom row of the left panel. Thus, significantly more children endured search until the end of the game in the 8-animals compared to the 1-animal condition (0.71 vs. 0.20, $\chi^2(1, N = 49) = 12.79$, $p < .001$, $BF = 207.9$). Finally, we regressed participants' age in months and their condition onto the number of opened doors in a Bayesian linear regression, extracting the posterior estimates of both variables' effects onto the number of doors opened. This analysis showed that children opened more doors overall the older they were ($\hat{\beta} = 3.867$, 95%HPD: $[1.69, 6.10]$), but that the effect of condition persisted even when controlling for age ($\hat{\beta} = 10.02$, 95%HPD: $[5.63, 14.33]$). We found similar results when regressing onto latency.

Study 2

Methods

Participants. We recruited 44 young children (range: 26 to 56 months, 17 female, $M_{\text{age}} = 37.41$; SD=7.56) from the Zoo in Berlin, Germany. Fourteen additional participants were excluded because they were distracted (n=2), could not operate the tablet (n=1), parental intervention (n=2), technical difficulties (n=7) or the child did not understand English (n=2). Informed consent was obtained from the parents of all participating children. Ethics approval for Study 2 and Study 3 was obtained by the ethical review board of the Max Planck Institute for Human Development, Berlin (protocol: Doors).

Design and Materials. Study 2 used exactly the same stimuli, and implemented the same procedure and design of Study 1, with one difference only: Instead of comparing an unknown-animal (8-animals) condition to a known-animal (1-animal) condition, we compared two unknown-animal conditions, in which children were told that the animal hiding could have been one of two (2-animals condition) or eight different animals (8-animals condition), but were not told which one. Note that the 8-animals condition is identical as in Study 1. The procedure and stimuli of Study 2 are illustrated in Fig. 1.

Results

As in Study 1, all measures converged to indicate that children were more persistent in their search when the information gain of their actions was higher, in the 8-animals compared to the 2-animals condition: They opened more doors on average (32.2 vs. 19.1 doors; $t(42) = 3.93$, $p < .001$, $d = 1.11$, $BF = 89.5$) and searched longer before showing signs of leaving (124.1 vs. 80.6 seconds; $t(32) = 2.49$, $p = .018$, $d = 0.86$, $BF = 6.36$), see Fig. 2, mid panel. Moreover, whereas 13 out of 22 participants reached the time limit in the 2-animals condition, 20 out of 24 did so in the 8-animals condition ($\chi^2(1, N = 46) = 4.37$, $p = .036$, $BF = 5.67$). Finally, as in Study 1, regressing children's age in months and their condition onto the number of opened doors showed that children opened more doors the older they were ($\hat{\beta} = 0.618$, 95%HPD: $[0.15, 1.08]$), and confirmed that the effect of condition persisted even when controlling for age ($\hat{\beta} = 10.50$, 95%HPD: $[3.52, 17.51]$).

Study 3

Methods

Participants. We recruited 24 young children (range: 37 to 48 months, 15 female, $M_{\text{age}} = 41.50$; SD=3.12) from the participants database of the Max Planck Institute for Human Development in Berlin. Six additional participants were excluded because of technical difficulties (n=3), or because they did not want to participate anymore (n=3). Informed consent was obtained from the parents of all participating children.

Design and Materials. In Study 3, we implemented three crucial changes to the main paradigm: First, we presented children with both conditions in a within-subjects design (order counterbalanced). To do that, we used two different sets of objects and cover stories (animals, as in Study 1 and 2, and toys, in counterbalanced assignment to conditions). Second, we implemented a small but crucial change to the procedure of the *1-animal/toy* condition, eliminating a potential confound from the previous studies: we showed children at the beginning *all eight* animals/toys, before telling them which one they were looking for. In this way, we could make sure that children understood the crucial difference between conditions, and that the observed differences could not be attributed to them simply being initially exposed to more objects in the *8-animals/toys condition*. Third, because of the restrictions related to the COVID-19 pandemic, the study was administered online through a video-conferencing platform. For this reason, children would have to say “Open!” [“Auf!” in German] to open the doors, instead of touching the doors on the screen. Also, as it was easier for children to get distracted in the online administration of the task, the session was ended if the child had not given up searching after 3 minutes, instead of 4 minutes as in the previous studies. The procedure was not altered in any other way. The procedure and stimuli of Study 3 are illustrated in Fig. 1.

Results

As in Study 1 and 2, all measures converged to indicate that children were more persistent in their search when the information gain of their actions was higher, in the 8-animals/toys compared to the 1-animal/toy condition (see Fig. 2, right panel): they opened more doors (25.5 vs. 20.2 doors; $t(23) = 3.44$, $p = .002$, $d = 0.70$, $BF = 34.91$) and searched longer before showing signs of leaving (88.35 vs. 63.7 seconds; $t(23) = 2.96$, $p = .007$, $d = 0.60$, $BF = 13.01$). Moreover, children reached the time limit in the 8-animals/toys condition more often as compared to the 1-animal/toy condition (20 out of 24 vs. 13 out of 22; $\chi^2(1) = 6.8275$, $p = .009$, $BF = 124.91$). Finally, regressing children's age in months and their condition onto the number of opened doors showed no effect of age ($\hat{\beta} = 0.20$, 95%HPD: $[-0.82, 1.22]$), but confirmed that the effect of condition again persisted when controlling for age ($\hat{\beta} = 5.29$, 95%HPD: $[2.27, 8.31]$).

Discussion

A challenging problem for intelligent systems is how to behave in scenarios with sparsely occurring, uncertain or no rewards. Yet, already very young children successfully cope with this challenge successfully. How do they accomplish this?

We studied children's persistence in a search task without rewards, manipulating across three studies the expected information gain of the same search action. Overall, our results robustly suggest that toddlers and preschoolers were more persistent in their search when there was more information to be gained. Note that this was true when contrasting *whether* the same action would yield additional information gain or not (Study 1), as well as when manipulating the *amount* of additional information gained (Study 2). Crucially, we obtained exactly the same results when conditions were manipulated within subjects (Study 3), indicating that the observed effects are robust and stable, even at the individual level. Thus, our work suggests that information gain is enough to drive young children's exploration, as an intrinsic reward, even in the absence of any other explicit rewards or observed outcomes.

These findings radically advance our understanding of children's motivation to learn and explore, and have strong implications for both developmental psychology and artificial intelligence. From the perspective of developmental psychology, this work puts forward a theory of children's exploration and learning that is driven by expected information gain and is able to explain previous results under a unifying framework. From the perspective of artificial intelligence, our findings suggest that to build machines that learn like children, one should build curiosity-based systems, designing algorithms that are motivated by the underlying information gain of their actions.

Data and code

All data and code to reproduce the results reported in this article can be found on github: https://github.com/ericschulz/doors

Acknowledgements

We thank Pamee Sapasap, Daniil Serko and Nele Metzner for help with data collection and coding, and Federico Meini for programming the experiment.

Author Contributions

AR conceived the idea. AR and ES designed the experiments. AR carried out the experiments. ES analyzed the data. AR and ES took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

References

Alvarez, A. L., & Booth, A. E. (2014). Motivated by meaning: Testing the effect of knowledge-infused rewards on preschoolers' persistence. *Child development*, *85*, 783–791.

Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive psychology*, *64*, 215–234.

Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental review*, *32*, 125–160.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PloS one*, *7*, e36399.

Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *Psychological bulletin*, *116*, 75.

Meder, B., Wu, C. M., Schulz, E., & Ruggeri, A. (2020). Development of directed and random exploration in children. *Developmental Science*, e13095.

Pathak, D., Agrawal, P., Efros, A. A., & Darrell, T. (2017). Curiosity-driven exploration by self-supervised prediction. In *Proceedings of the ieee conference on computer vision and pattern recognition workshops* (pp. 16–17).

Ruggeri, A., Sim, Z. L., & Xu, F. (2017). "Why Is Toma Late to School Again?" Preschoolers Identify the Most Informative Questions. *Developmental Psychology*, *53*, 1620–1632. doi: 10.1037/dev0000340

Ruggeri, A., Swaboda, N., Sim, Z. L., & Gopnik, A. (2019). Shake it baby, but only when needed: Preschoolers adapt their exploratory strategies to the information structure of the task. *Cognition*, *193*, 104013.

Schmidhuber, J. (2010). Formal theory of creativity, fun, and intrinsic motivation (1990–2010). *IEEE Transactions on Autonomous Mental Development*, *2*, 230–247.

Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019). Searching for rewards like a child means less generalization and more directed exploration. *Psychological Science*, *30*, 1561-1572.

Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: preschoolers engage in more exploratory play when evidence is confounded. *Developmental psychology*, *43*, 1045.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*, 91–94.

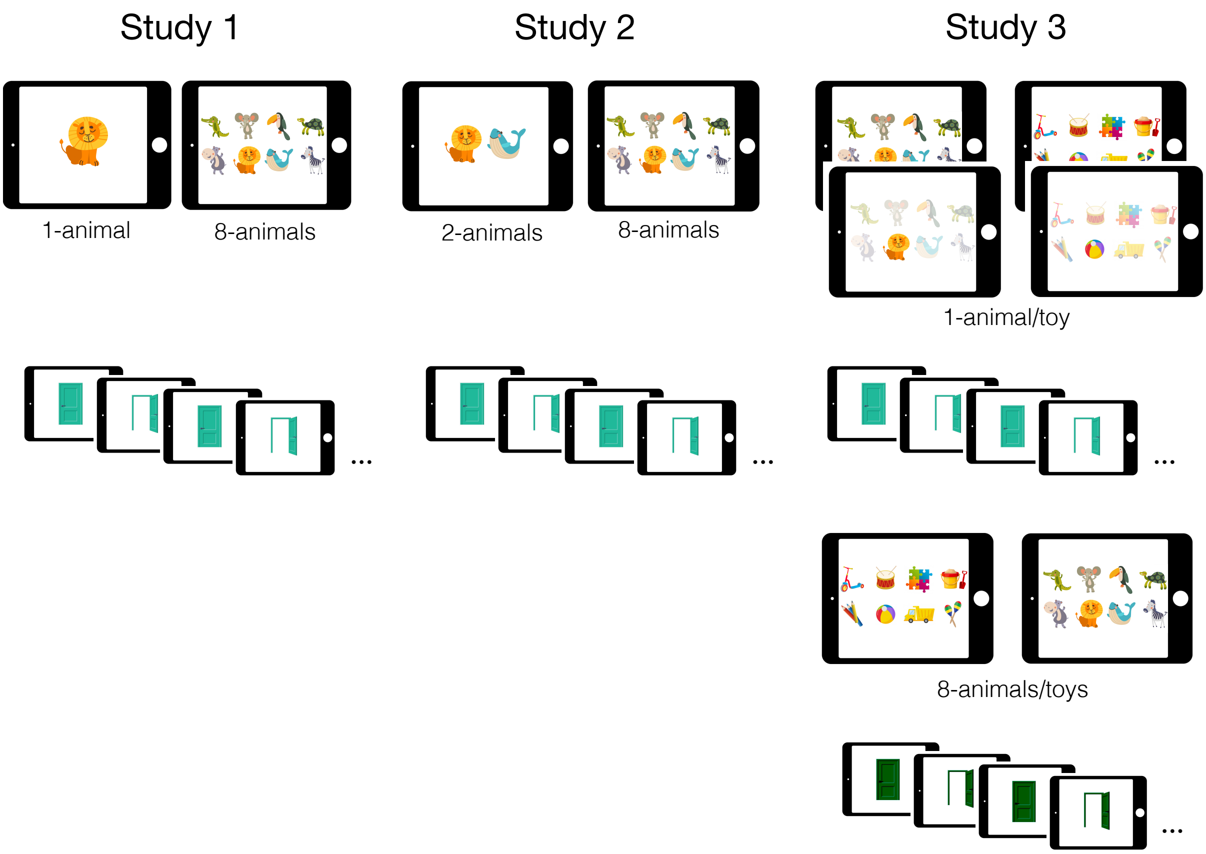

Figure 1. Illustration of the stimuli and procedure used in Study 1 (left), Study 2 (middle) and Study 3 (right). Whereas in Study 1 and 2 conditions were assigned between subjects, in Study 3 they were manipulated within subjects (order of conditions counterbalanced; sets of animals and toys stimuli in counterbalanced assignment to conditions).

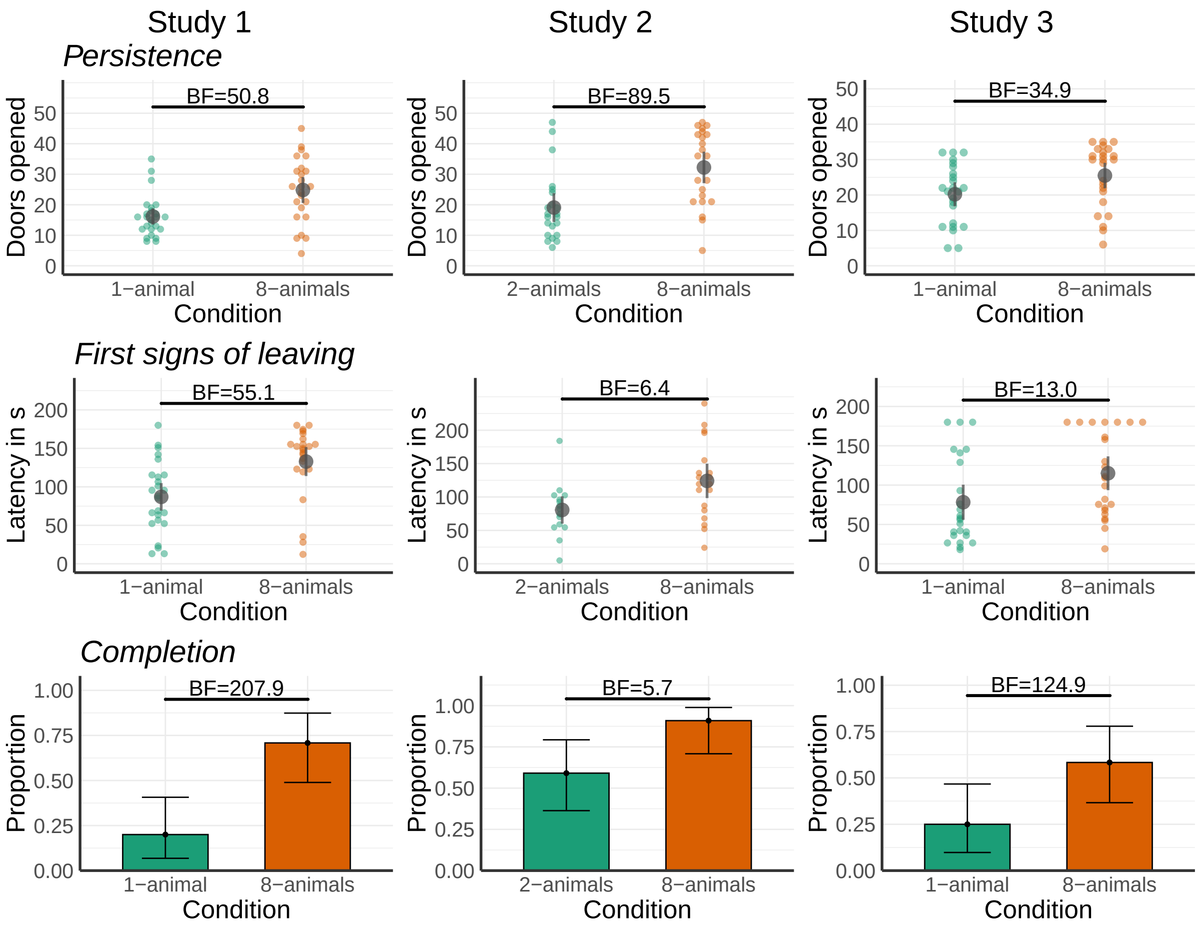

Figure 2. Results of Study 1 (left), Study 2 (middle) and Study 3 (right). Top row: Total number of doors opened by condition. Mid row: First signs of leaving, measured as the latency in seconds from the beginning of the search to the point at which children first signaled that they wanted to give up searching. Dots indicate individual participants. Black dot and error bars indicate the group mean and the 95% confidence intervals. Bottom row: Proportion of children searching until the predetermined time limit. Error bars represent the 95% confidence interval of a binomial distribution. All figures also show the resulting Bayes Factor when comparing the two conditions.