How social contexts shape active learning

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Abstract

Children's rapid conceptual development is one of the more remarkable features of human cognition. How do they learn so much so quickly? Social learning theories argue for the importance of learning from more knowledgeable others. In contrast, active learning accounts focus on children's knowledge acquisition via thei self-directed exploration. In this paper, I argue that an important step towards a more complete theory of early learning is to understand how active learning behaviors unfold in social learning contexts. To integrate the two theoretical accounts, I use ideas from theories of rational decision making that emphasize the expected utility and cost of different actions in order to explain choice behavior. The key insight is that the costs and benefits of active learning behaviors (e.g., metacognitive monitoring, spontaneous exploration, and question asking) are fundamentally shaped by interactions with other people.

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Introduction

Human learning is remarkable. Consider that children, despite limitations on their general processing capabilities, are able to acquire new concepts at a high rate, eventually reaching an adult vocabulary ranging between 50,000 to 100,000 words (P. Bloom, 2002). And they accomplish this while also developing motor skills, learning social norms, and building causal knowledge. What sorts of processes can account for children's prodigious learning abilities?

Social learning theories offer a solution by pointing out that children do not solve these problems on their own. And although children learn a great deal from observation, they are typically surrounded by parents, other knowledgeable adults, or older peers – all of whom likely know more than they do. These social contexts can bootstrap learning via several mechanisms. For example, work on early language acquisition shows that social partners provide input that is tuned to children's cognitive abilities (Eaves Jr, Feldman, Griffiths, & Shafto, 2016; Fernald & Kuhl, 1987), that guides children's attention to important features in the world (C. Yu & Ballard, 2007), and that increases levels of arousal and sustained attention, which lead to better learning (P. K. Kuhl, 2007; C. Yu & Smith, 2016).

Social contexts can also change the computations that support children' learning from evidence. Recent work on both concept learning and causal intervention suggests that the presence of another person leads the learner to reason about *why* people perform certain actions. The key insight is that knowledge of the underlying process that generates examples allows learners to make more appropriate inferences that speed learning (E. Bonawitz & Shafto, 2016; Frank, Goodman, & Tenenbaum, 2009; Shafto, Goodman, & Griffiths, 2014). For example, people will draw different inferences from observing the same actions depending on whether they think that the behavior was accidental or intentional. Moreover, adults and children will make even stronger inferences if they think an action was selected with the goal to help them learn (i.e., teaching) (Shafto, Goodman, & Frank, 2012).

However, children are not merely passive recipients of information – from people or from the world. Instead, children actively select behaviors (e.g., asking questions or choosing where to allocate attention) that change the content, pacing, and sequence of the information that they receive. In fact, recent theorizing and empirical work uses the metaphor of "child as intuitive scientist" and characterizes early learning asa process of exploration and hypothesis testing following principles of the scientific method (Gopnik, Meltzoff, & Kuhl, 1999; L. Schulz, 2012). Moreover, recent empirical work across a variety of domains (education, machine learning, and cognitive science) has begun to directly compare the benefits of self-directed choice compared to passive contexts for speeding learning outcomes via increases in learners' basic learning processes (attention and arousal) or by providing learners with better information that is more tightly linked to their current beliefs, goals, and interests (Castro et al., 2009; D. B. Markant & Gureckis, 2014; Settles, 2012).

Thus, both social and active learning accounts argue that cognitive development is facilitated by the activation of distinct learning processes and by the learner gaining access to better information from the environment. However, children's learning often involves a mixing of active behaviors (choices) with social contexts where other people respond to children's actions. Thus, an efficient learner must integrate information that they generate with information provided by other people to decide what to do next. Thus, one of the fundamental challenges for building a complete theory of human learning is to characterize the effects of social contexts on self-directed learning behaviors.

In this paper, I take a step towards the goal of integrating pieces of the active and social learning accounts. To do this, I will use the framework of Optimal Experiment Design (Emery & Nenarokomov, 1998), which provides a useful formalization of human inquiry. One of the key insights is that social learning contexts can help to *scaffold* the decision processes (i.e., choices) that confronts a self-directed learner. I also propose that findings from social learning research provide a way to explain a set of puzzles in the study of children's uncertainty monitoring (markman; kim et al.), spontaneous information seeking (begus; Deaf of Hearing social referencing), and verbal question asking (katz et al. (2010). Before presenting the integrative account of active and social learning, it is useful to review the evidence showing that both social contexts (Part 1) and self-directed learning behaviors (Part 2) fundamentally change how learning unfolds.

Part I: Learning from other people

Social learning theories argue that children's rapid conceptual development is facilitated by humans' unique capacity to transmit and acquire information from other people.[1] One of the primary benefits of cultural learning is that children gain access to knowledge that has accumulated over many generations; information that would be far too complex for any individual person to figure out on their own (Boyd, Richerson, & Henrich, 2011). In addition to these cumulative effects, social contexts facilitate learning because more knowledgeable others select the input that could best support children's learning (Kline, 2015; Shafto et al., 2012), providing learning opportunities for generalizable information (Csibra & Gergely, 2009).

There is now a large body of empirical work on children's learning that show the effect of social contexts across a variety of domains. These learning effects manifest via different pathways such as guiding attention, increasing arousal, providing better information, and changing the strength of children's inferences. In this section, I briefly review the evidence for the role of each of these social learning processes, with the goal of providing a high-level taxonomy of social learning effects. Outlining these social learning effects will set the stage for the discussion of how they shape self-directed learning behaviors in Part III.

Social interactions enhance attention and memory. From infancy humans preferentially attend to social information. For example, newborn infants will choose to look at face-like patterns compared to other abstract configurations (Johnson, Dziurawiec, Ellis,

[1] In this paper, I define "social" contexts as learning environments where another agent is present. This definition includes a broad range of social learning behaviors: e.g., observation, imitation, and learning from direct pedagogy.

& Morton, 1991) and will even show a preference for faces that make direct eye contact compared to faces with averted gaze (Farroni, Csibra, Simion, & Johnson, 2002). In the auditory domain, newborns prefer to listen to speech over non-speech (Vouloumanos & Werker, 2007), their mother's voice over other voices (DeCasper, Fifer, Oates, & Sheldon, 1987), and infant-directed speech over adult-directed speech (Cooper & Aslin, 1990; Fernald & Kuhl, 1987; Pegg, Werker, & McLeod, 1992). And recent work by C. Yu and Smith (2016) using head-mounted eye trackers to record parent-child interactions found that one-year-olds will sustain visual attention to an object longer when their parents' had previously looked at that object.

These early attentional biases can lead to differential outcomes when learning occurs with another person present. For example, 4-month-olds' show better memory for faces if that face gazed directly at them as compared to memory for a face with averted gaze (Farroni, Massaccesi, Menon, & Johnson, 2007) and for objects if an adult gazed at that object during learning (Cleveland, Schug, & Striano, 2007; Reid & Striano, 2005). Moreover, 7-month-olds perform better at word segmentation if the words are presented in infant-directed speech compared to adult-directed speech (Thiessen, Hill, & Saffran, 2005).

P. K. Kuhl (2007) refer to these effects as "social gating" phenomena since the presence of another person activates or enhances children's underlying computational learning mechanisms such as attention. One particularly striking piece of evidence for the social gating hypothesis comes from P. K. Kuhl, Tsao, and Liu (2003)"s study of infants" foreign-language phonetic learning. In this experiment, 9-10 month-old English-learning infants listened to Mandarin speakers either via live interactions or via audiovisual recordings and their ability to discriminate Mandarin-specific phonemes was assessed two months later. Only the infants who were exposed to Mandarin within social interactions were able to succeed on the phonetic discrimination task and infants in the audiovisual recording condition showed no evidence of learning. P. K. Kuhl et al. (2003) also provided evidence that infants in the social interaction condition showed higher rates of visual attention to the speaker, suggesting that the social contexts enhanced learning by increasing children's attention to the input.

The common thread across these findings is that the presence of another person is a particularly good way to increase attention. In this model, social input becomes more salient and therefore more likely to come into contact with general learning mechanisms. However, increases in arousal, attention, and memory are only one way that social contexts can influence learning. In fact, one of the defining features of early learning environments is the presence of other people who know more than the child, creating opportunities for more knowledgeable others to select learning experiences that are particularly beneficial – either because the information is tuned to children's current cognitive abilities or because the information is likely to be generalizable.

Social interactions provide "good" information. The notion that children's input might be shaped to facilitate their learning is a key tenet of several influential theories of cognitive development (e.g., Zone of Proximal Development (Vygotsky, 1987), Guided Participation (Rogoff et al., 1993), and Natural Pedagogy (Csibra & Gergely, 2009)). But how do social interactions provide particularly useful information for children's learning?

A particularly compelling set of evidence comes from studies of how caregivers alter the way they communicate with young children. That is, adults do not speak to children in the same way as they speak to other adults; instead, they exaggerate prosody, reduce speed, shorten utterances, and elevate both pitch and affect (for a review, see (Fernald & Simon, 1984)). And subsequent empirical work has shown that these features of "infant-directed speech" facilitate vowel learning (Adriaans & Swingley, 2017; De Boer & Kuhl, 2003), word segmentation (Fernald & Mazzie, 1991; Thiessen et al., 2005), word recognition (Singh, Nestor, Parikh, & Yull, 2009), and word learning (Graf Estes & Hurley, 2013).

Work on infants' early vocal production also provides evidence for the importance social feedback, highlighting the feature of *contingency*. For example, Goldstein and Schwade (2008) measured whether infants modified their babbling to produce more speech-like sounds after interacting with caregivers who either provided contingent or non-contingent responses to infants' babbling. They found that only infants in the contingent feedback condition changed their vocalization behavior to produce more adult-like language forms. Goldstein and Schwade (2008) hypothesized that the contingency effect was driven by infants' receiving input that was particularly useful for solving this learning problem since the feedback was close in time to infants' vocalizations, making it easier for them to compare discrepancies between the two.

A third piece of evidence comes from research on children's early word learning. Social-pragmatic theories of language acquisition have emphasized the importance of social cues for reducing the (in principle) unlimited amount of referential uncertainty present when children are trying to acquire novel words (P. Bloom, 2002; Clark, 2009; Hollich et al., 2000). Empirical work by C. Yu and Smith (2012a) shows that young learners tend to retain words that are accompanied by clear referential cues, which serve to make a single object dominant in the visual field (see also (C. Yu & Smith, 2013; C. Yu, Ballard, & Aslin, 2005). Moreover, correlational studies show positive links between early vocabulary development and parents' tendency to refer to objects that children are already attending to (i.e., "follow-in" labeling) (Tomasello & Farrar, 1986).

Thus far, I have reviewed evidence showing that social information can benefit learning because it enhances attention and it contains features that make it easier to learn. Learning from other people also changes learning by engaging distinct social reasoning processes that change how learners interpret and learn from evidence.

Social interactions influence inferences and generalization. Perhaps one of the defining features of human social learning is that teachers and learners' actions are not random. Instead, people select behaviors with respect to some goal (e.g., to communicate a concept), and learners reason about *why* someone chose to perform a particular action. The key point is that this reciprocal process of reasoning about others' goal-directed actions can change how people interpret superficially similar behaviors, altering the learning process.

In recent empirical and modeling work, Shafto et al. (2012) formalized this social reasoning process within the framework of Bayesian models of cognition. In these models, learning is a process of belief updating that depends on two factors: what the learner believed before seeing the data and what the learner thinks about the process that generated the data. The key insight is that if the learner assumes that information is generated with the intention to communicate/teach, then they can make "stronger" inferences.[2]

For example, Goodman, Baker, and Tenenbaum (2009) presented adults with causal learning scenarios with the following structure: either the participant or someone else who knows the causal structure generates an effect (e.g., growing flowers) by performing two actions at the same time (e.g., pouring a yellow liquid and a blue liquid). The participant's task was to identify the correct causal structure. Results showed that when participants thought the other person was knowledgeable, they were more likely to infer that performing *both* actions was necessary. In contrast, when the participant performed the action on their own (and did not know the causal structure), adults were less sure that both actions were necessary. Shafto et al. (2012) interpreted these results as learners going through a psychological reasoning process such as "if the other person was knowledgeable and wanted to generate the effect, he would definitely perform both actions if that was the correct causal structure."

Similar psychological reasoning effects have been shown in the domains of word learning (Frank & Goodman, 2014; Xu & Tenenbaum, 2007), selective trust in testimony (Shafto, Eaves, Navarro, & Perfors, 2012), tool use (Sage & Baldwin, 2011), and concept learning (Shafto et al., 2014). Moreover, there is evidence that even young learners are sensitive to the presence of others' goal-directed behaviors. For example, Yoon, Johnson, and Csibra (2008) showed that 8-month-olds will encode an object's identity if their attention was directed by a communicative point, but they will encode an object's spatial location if their

[2]Formally, these models change the form of the likelihood term in Bayes theorem in order to capture a person's theory of how data are generated.

attention was directed by non-communicative reach. And Senju and Csibra (2008) found that infants will follow another person's gaze only if the gaze event was preceded by the person providing a relevant, communicative cue (e.g., infant-directed speech or direct eye contact).

In addition to being easier to learn, information acquired in social contexts is also more likely to generalize and be useful beyond the current learning context. Csibra and Gergely (2009) argue that this assumption of *generalizability* is a fundamental component of "Natural Pedagogy" – a uniquely human communication system that allows adults to efficiently pass along cultural knowledge to children. Experimental work testing predictions from this account shows that children are biased to think that information presented in communicative contexts is generalizable (Butler & Markman, 2012; Yoon et al., 2008), and corpus analyses provide evidence that generic language (e.g., "birds fly") is common in everyday adult-child conversations (Gelman, Goetz, Sarnecka, & Flukes, 2008).

Across all of these studies, learners interpreted similar information in different ways depending on their assumptions about other people's goals. These effects are different from the attentional and informational explanations reviewed above in that the inferences based on social information are part of the underlying computations that support learning. This account fits well with evolutionary models that emphasize the importance of pedagogy for the accumulation of human cultural knowledge (Boyd et al., 2011; Kline, 2015) and theories of cognitive development that emphasize the adult's role as providing children with generalizable information (Csibra & Gergely, 2009).

Part II: Learning on your own

Another key ingredient for children's rapid conceptual development is their ability to learn on their own. That is, children are not just passive recipients of information; instead, they actively seek knowledge via their own actions. This model of the child as an "active" learner has been an influential idea in many classic theories of cognitive development (e.g., Bruner (1961); Berlyne (1960)). And recent theorizing has characterized cognitive development as a process of active hypothesis testing and theory revision following principles similar to the scientific method (Gopnik et al., 1999; L. Schulz, 2012).

In addition to playing a prominent role in developmental theory, the potential benefits of "active"[3] learning have been the focus of a great deal of empirical work in education (Grabinger & Dunlap, 1995; Prince, 2004), machine learning (Ramirez-Loaiza, Sharma, Kumar, & Bilgic, 2017; Settles, 2012), and cognitive psychology (Castro et al., 2009; Chi, 2009). The common finding across these studies is that active learning contexts – where people have control over some aspect of the learning environment – lead to better outcomes when compared to passive contexts where people do not have control over the information that they receive.

But what makes active control a useful way to learn about the world? In this section, I present evidence for two mechanisms – enhanced attention/memory and higher quality information – through which active control can improve learning outcomes. I then review work that formalizes human inquiry as a process of "optimal experiment design" (OED) to ask when and how human self-directed learning deviates from optimal information gathering principles. I conclude Part II with a discussion of what makes optimal active learning difficult and why this is an intresting point of contact with research on children's social learning.

Active control enhances attention and memory. A growing body of work has explored the effect of active control on basic processes underlying learning and memory. In these tasks, outcomes for active and passive learning experiences are directly compared across a variety of tasks, such as episodic memory, casual learning, and concept learning. D. B. Markant, Ruggeri, Gureckis, and Xu (2016) review this diverse literature and suggest that the active learning advantage found across these domains is caused by an increase in

[3]The term "active learning" has been used to describe a wide variety of behaviors such as question asking, increased physical activity, or active memory retrieval. In this paper, I focus on a specific subset of these behaviors: the *decisions* that people make, or could make, during learning. This definition captures several ways that people can exert control over their learning experiences, including the selection, sequencing, and/or pacing of new information.

attention and memory with the precise pathway determined by the type of control in the study. For example, one effect of active control is that is allows people to coordinate the timing of incoming information with their current cognitive state, including attention and readiness to learn.

One nice illustration of this effect comes from a study by D. Markant, DuBrow, Davachi, and Gureckis (2014). In this task, participants memorized the identities and locations of objects that were hidden in a grid (adapted from Voss et al. (2011)). D. Markant et al. (2014) varied the *level* of control across conditions and compared the performance of active learners to a group of "yoked" participants who saw training data that was generated by the active group. Across conditions, participants could either control: (a) the next location in the grid, (b) the next item to be revealed, (c) the duration of each learning trial, and/or (d) the time between learning trials (i.e., inter-stimulus-interval or ISI). Results showed an active learning advantage for all levels of control, including the lowest amount of control in the ISI-only condition. D. Markant et al. (2014) interpreted these results as providing evidence that active control allowed people to, "optimize their experience with respect to short-term fluctuations in their own motivational or attentional state."

Developmental studies have extended this work on adults' spatial memory to 6- to 8-year old children, showing similar advantages for conditions of active control (Ruggeri, Markant, Gureckis, & Xu, 2016). Other work has found similar benefits of active control in word learning (Partridge, McGovern, Yung, and Kidd (2015); see also Kachergis, Yu, and Shiffrin (2013) for evidence in adults) and understanding causal structures (L. Schulz, 2012). Sobel and Kushnir (2006) showed that learners who designed their own interventions on a causal system learned better than yoked participants who either passively observed the same sequence of actions or re-created the same choices made by others. Moreover, even young infants seem to benefit from active engagement with the learning environment. For example, Begus, Gliga, and Southgate (2014) showed that 16-month-old infants show evidence of stronger memory for information that was provided about an object they had previously pointed to as opposed to information about an object they had previously ignored.

Additional evidence that active control enhances attention and memory comes from research on children's engagement with educational technology (for a review, see Hirsh-Pasek et al. (2015)). For example, Calvert, Strong, and Gallagher (2005) exposed preschool-aged children to two sessions of reading a computer storybook with an adult, and manipulated whether the adult or the child controlled the mouse and could advance the story. Children in the adult-control condition showed a decrease in attention to the storybook materials in the second session; in contrast, children who were given control over the experience maintained similar levels of attention across both sessions. Other research shows that when adults interact with an avatar that is controlled by a real person rather than a computer, people experience higher levels of arousal, learn more, and pay more attention (Okita, Bailenson, & Schwartz, 2008). And work by Roseberry et al. (2014) showed children learned equally well from interactions with a person in a video chat (e.g., Skype) when social contingency was established, but they did not learn from watching a digital interaction between the adult and another child.

These results parallel the literature on attention/memory effects in social learning reviewed in Part 1. That is, both active and social processes can modulate attention and memory to facilitate in-the-moment learning. However, as in social learning, the effects of active control operate through multiple mechanisms, going beyond changes in lower-level cognitive processes to changing the quality of *information* that learners get from the world.

Active control provides "good" information. Active learning allows people to gather information that is particularly "useful" for their own learning. This benefit relies on the fact that learners have better access to their own prior knowledge, current hypotheses, and ability level, which they can leverage to create more helpful learning contexts (e.g., asking a question about something that is particularly confusing). Research on this component of active learning focuses on how learners select actions to create experiences that are more useful compared to entirely passive contexts where the learner has less control.

For example, Castro et al. (2009) directly compared adult active and passive category learning to predictions from statistical learning theory under conditions of varying difficulty. They found that human active learning was always superior to passive learning, but did not reach the performance of the optimal model and the advantage for active control decreased in the more difficult (i.e., noisier) learning tasks. Using a similar model-based approach, D. B. Markant and Gureckis (2014) investigated the effects of active vs. passive hypothesis testing on the rate of adults' category learning. They varied the difficulty of the learning task by testing two different types of category structures: a rule-based category, which varied along 1 dimension (easier to learn), and an information-integration category, which varied along 2 dimensions (harder to learn). In the active condition, the learner chose specific observations from the category to test his or her beliefs, whereas in the passive condition, the data were generated randomly by the experiment. Participants in the active condition learned the category structure faster and achieved a higher overall accuracy rate compared to participants in the passive learning condition, but only for the simpler, rule-based category.

Together, the Castro et al. (2009) and D. B. Markant and Gureckis (2014) results illustrate several important points about active learning. First, the quality of active exploration was fundamentally linked to the learner's understanding of the task: if the representation was poor, then self-directed learning was biased and ineffective. Second, the benefits of active control were tied to the aspects of the individual learner – i.e., their prior knowledge and the current hypotheses under consideration – such that the same sequence of data did not provide "good" information for another learner. And third, the benefits of active learning diminished with increased task difficulty, perhaps because learners struggled to generate "helpful" examples.

A recent body of developmental work on children's pointing has begun to explore how children's actions can change the flow of information to support their later learning. For example, Wu and Gros-Louis (2015) found that adults generate a higher number of object labels for objects that their 12-month-olds pointed to, suggesting that the infants' pointing elicited information that was more useful for early word learning (for converging evidence, see Kishimoto, Shizawa, Yasuda, Hinobayashi, and Minami (2007); Goldin-Meadow, Goodrich, Sauer, and Iverson (2007); and Olson and Masur (2011)). In addition, experimental by Begus and Southgate (2012) showed that infants point more in the presence of a knowledgeable person compared to an incompetent person, which suggests that children's behavior is driven by a desire to learn something new as opposed to just share attention with another person. Finally, infants early pointing behaviors have been directly linked to their later language learning (Rowe & Goldin-Meadow, 2009), providing additional evidence that pointing elicits language that is particulary helpful for building early vocabulary.

A little later in development, after children develop the requisite productive language skills, they begin to generate verbal questions. And there is reason to believe that children are using questions to gather "good" information from other people. For example, in a corpus analysis of four children's parent-child conversations, Chouinard, Harris, and Maratsos (2007) found that children begin asking questions early in development (18 months) and at an impressive rate, ranging from 70-198 questions per hour of conversation. Chouinard et al. (2007) also coded the intent of children's questions, finding that 71% were for the purpose of gathering information, as opposed to attention getting or clarifications. Other corpus analyses provide converging evidence that question asking is a common behavior in parent-child conversations (Davis, 1932), that children are seeking knowledge with their questions (Bova & Arcidiacono, 2013), and that children will persist in asking questions if they do not receive a satisfactory explanation (Frazier, Gelman, & Wellman, 2009).

Perhaps the best evidence that children are capable of effective self-directed learning comes from research on children's active behaviors in causal learning tasks. In these studies, children are often presented with a novel toy that has some unknown causal structure, and they are then given the opportunity to design interventions to figure out how the toy works. For example, Cook, Goodman, and Schulz (2011) showed preschoolers a device that played music when beads were placed on top of it. To test whether children would choose interventions that generated useful information about the causal structure work, they manipulated the usefulness of different actions children could choose to test the devide. That is, half of the children were trained to think that all different types of beads could make the machine work, while the the other half of children learned that only certain types of beads could make it go. Next children were given the opportunity to choose their own beads to try to make the machine play music, and could chose either: (1) a set of two beads that were stuck together or (2) a set of two beads that could be separated. Results showed that children who learned that only *some* of the beads worked were twice as likely to choose the separable beads to test the device, suggesting that they were sensitive to the fact that there was information to be gained by choosing this behavior (i.e., they could pull the beads apart and test each one independently).

Other work in the domain of causal inference shows that preschoolers can integrate prior beliefs and evidence to alter how they explore a causal system to learn something like balance-relations (E. B. Bonawitz, Schijndel, Friel, & Schulz, 2012); that when preschoolers see confounded evidence for how something works, they spend more time exploring that object (Schulz & Bonawitz, 2007); that even 8-month-old infants will selectively explore objects that violate their prior expectations (Stahl & Feigenson, 2015); and that children became more efficient in producing causal interventions, as measured by their informativeness, as they get older (McCormack, Bramley, Frosch, Patrick, & Lagnado, 2016).

Another early behavior that appears sensitive to the value of seeking certain kinds of information is visual and auditory attention. This research starts from two assumptions: one that children possess limited cognitive resources with which to process information from the world, and (2) that efficient learning is faciliated by attending to information that is particularly likely to be learned, i.e., useful. For example, Kidd, Piantadosi, and Aslin (2012) took measured how long 7- and 8-month-olds visually attended to a monitor that displayed a sequence of images of familiar objects (e.g., a toy truck). Within each sequence, infants saw trials that varied along a continuum from low to high complexity, with the complexity of specific trial defined using a model-based approach that took into account the prior objects that infants saw in the sequence and quantified how surprising the current object was. Infants spent the most time looking on trials of intermediate complexity, choosing to look away sooner when the object was either highly predictable or highly surprising based on the prior sequence of objects. Kidd, Piantadosi, and Aslin (2014) extended these results to the auditory domain, showing a similar pattern of increased attention to intermediate complexity for sequences of nonsocial sounds such as a door closing or a train whistle. One interpretation of these results is that infants' in-the-moment visual and auditory attention leverages their prior experiences to focus on specific information that is likely to be learned

In addition to seeking learnable information, infants also show evidence of avoiding information that is unlearnable. For example, Gerken, Balcomb, and Minton (2011) tested whether 17-month-olds would pay more attention to a stream of input that consisted of a learnable structure (e.g., Russian feminine words take the endings oj and u, and masculine words take the endings ya and yem) as opposed to a random stream of input without any information to extract (e.g., word endings were not diagnostic of category structure). Results showed that infants were quicker to disengage attention from the unlearnable information stream, suggesting that they were doing some form of tracking their own learning progress, using this estimate to decide to stop gathering information when learning progress was sufficiently low.

Taken together, the findings reviewed in this section highlight two points. First, from an early age children are capable of engaging in behaviors that appear to serve the goal of seeking useful information to support learning. Second, these findings illustrate the complexity of studying self-directed learning. That is, many behaviors can be cast as examples of self-directed learning, and it is not the case that active learning functions similarly across individuals, contexts, and learning domains. Moreover, there are a multitude of factors that could modulate the effectiveness of active learning behaviors, creating a large set of possibilities for researchers to explore.

One way to get a handle on this complexity is to develop a formal model of human active learning that abstracts away some detail in order to gain access to general principles that shape active learning behaviors. Recently, researchers in both developmental and cognitive psychology have taken advantage of the development of formal models of scientific inquiry by statisticians (Optimal Experiment Design or OED models) in order to select the best experiment from a set of possible experiments that a researcher could conduct when trying to learn about a new phenomenon. With this formallization in hand, researchers are able to make qualitative and quantiative comparisons to people's information seeking behavior, targeting specific components of the OED models with experiments and asking when/why people deviate from the optimal active learning behavior.

Optimal Experiment Design: A formal account of active learning. Optimal Experiment Design (OED) (Emery & Nenarokomov, 1998; Lindley, 1956; Nelson, 2005) is a statisical framework that attempts to quantify the "usefulness" of each experiment within the set of possible experiments that an experimenter could conduct to improve their understanding of a phenomenon. The key insight was described by Lindley (1956) as a transition from viewing the practice of statistics as making binary decisions about what to do next to the practice of gathering information in order to sharpen one's understanding of the "state of nature" (p. 987), More concretely, he proposed that experiments should be designed to maximize a measure of expected information gain (taken from Information Theory and discussed in more detail below) and that researchers should continue the experiment until some pre-determined threshold of information is reached.

The benefit of using the OED approach is that it allows scientists to make design choices that maximize the effectiveness of their experiments, thereby reducing inefficiency and the costs related to additional experimentation. For example, Nelson, McKenzie, Cottrell, and Sejnowski (2010) used OED principles to differentiate competing theories of information seeking during adults' category learning. That is, they wrote down an OED model of their category learning task (classifying a set of images into one of two categories), the possible design choices (e.g., what combination of features to show participants), and the relevant behavioral hypotheses (i.e., different theories of category learning). And using this model, they were able to figure out the feature combinations for their stimuli on whichthe competing theories made different predictions, allowing them to

A growing body of psychological research has used the OED framework as a metaphor for human active learning. The idea is that when people make decisions about how to act on the world, they are engaging in a similar process of evaluating the "goodness" of these different actions (i.e., experiments) relative to some learning goal, and in turn, select behaviors that maximize the potential for gaining information about the world. One of the major successes of the OED model is that it can be used to account for a wide range of information seeking behaviors, including verbal question asking (Ruggeri & Lombrozo, 2015), planning interventions in causal learning tasks (Cook et al., 2011), and decisions about visual fixations during scene understanding (Najemnik & Geisler, 2005).

Coenen, Nelson, and Gureckis (2017) provide a thorough review of the OED framework and its links to research on the psychology of human information seeking. In their review, they lay out the four critical parts of an OED model: 1) a set of hypotheses, 2) a set of questions (i.e., actions) to learn about the hypotheses, 3) a way to model the types of answers that each question could elicit, and 4) a way to score each of the possible answers with respect to some usefulness metric. In addition to these components, they highlight the importance of learners' inquiry goal (e.g., "What's that object called?") for engaging in OED-like reasoning. The key point is that without a clear goal, then it becomes difficult to instantiate the hypotheses, questions, and answers that a learner should consider when deciding how to act. Next, I provide the mathematical details of the OED approach as described in Coenen et al. (2017). The goal of laying out the formal model in detail is to provide a structure for Part III where I discuss how social learning contexts can intervene on the different components of the OED model.

Together, the pieces of an OED model allow researchers to quantify the *expected utility* of a particular information seeking behavior such as a question $EU(Q)$) amongst a set of questions that a person could ask $Q_1, Q_2, ..., Q_n = \{Q\}$. The expected utility is a function of two factors: (1) the probability of obtaining a specific answer to a question $P(a)$ weighted by (2) the usefulness of that answer for achieving the learner's goal $U(a)$. Taken together, we can define the expected utility for a specific question Q as the sum of all utilities for all the possible answers to that question.

$$EU(Q) = \sum_{a \in q} P(a)U(a)$$

There are a variety of ways to define the usefulness function to score each answer. An exhaustive review is beyond the scope of this paper, but for a detailed analysis of different approaches to modelling the usefulness of actions with respect to information seeking, see Nelson (2005). One common approach is to use *information gain* defined as the change in the learner's overall uncertainty before and after receiving an answer. One way to instanstiate this calculation is to take the change from prior to posterior entropy (i.e., uncertainty) after getting a particular answer.

$$P(h|a) = ent(H) - ent(H|a)$$

Where the prior entropy $ent(H)$ can be defined as Shannon entropy, which provides a measure of the overall amount of uncertainty in the learner's beliefs about the candidate hypotheses.

$$ent(H) = -\sum_{h \in H} P(h) log P(h)$$

The posterior entropy $ent(H|a)$ is the entropy conditioned on a specific answer.

$$ent(H|a) = -\sum_{h \in H} P(h|a) log P(h|a)$$

And the $P(h|a)$ can be calculated using Bayes rule.

$$P(h|a) = \frac{P(h)P(a|h)}{P(a)}$$

If all pieces of and OED model are defined (hypotheses, questions, answers, and the usefulness function), then selecting the optimal question is straightforward. All the learner must do is perform the expected utility computation for each question in the set of possible questions and pick the one that maximizes utility, or is most useful for their learning goal. In practice, the learner must consider each possible answer, score the answer using the usefulness function, and weight the score using the probability of getting that answer.

There are several benefits of the OED formalization for understanding human active learning. First, it makes researchers define the different components of an active learning problem, thus making their assumptions about the phenomenon more explicit. Second, if researchers can develop an OED model, then they can ask whether people's behavior matches or deviates from the optimal behavior predicted by the model. Finally, casting information seeking as rational *choice* links psychology with several rich literatures (economics, statistics, computer science) that have attempted to formalize the decision-making process as a process of utility analysis that can include both the costs of information acquisition and the benefits of choosing a particular behavior.

One nice demonstration of this approach comes from Nelson (2005) model of eye movements during novel concept learning. The model combines Bayesian probabilistic learning, which represents the learner's current knowledge as a probability distribution over a concept, with an OED model of the usefulness of a particular eye movement (modeled as a type of question-asking behavior) for gathering additional information about the target concept from the visual world. Together, these model components allowed Nelson (2005) to predict changes in the pattern of eye movements at different time points in the learning task. Specifically, they found that early in learning, when the concepts were unfamiliar, the model predicted a wider, less efficient distribution of fixations to all candidate features that could be used to categorize the stimulus. However, after the model learned the target concepts, eye movement patterns shifted, becoming more efficient and focusing on a single stimulus dimension.

Another promising aspect of the OED models is that recent developmental work has provided evidence that even young children appear to select behaviors that efficiently maximize learning goals. Experimental work has investigated the quality of children's question asking by measuring the quality of questions in constrained problem-solving tasks. For example, Legare, Mills, Souza, Plummer, and Yasskin (2013) used a modified question asking game where 4- to 6-year-old children saw 16 cards with a drawing of an animal on them. The animals varied along several dimensions, including type, size, and pattern on the animal. The child's task was to ask the experimenter yes-no questions in order to figure out which animal card the experimenter had hidden in a special box. Legare et al. (2013) coded whether children asked constraint-seeking questions that narrowed the set of possible cards by increasing knowledge of a particular dimension or dimensions (e.g., "Is it red?"), confirmatory questions that provided redundant information, or ineffective questions that did not provide any useful information (e.g., "Does it have a tail?"). Results showed that all age groups asked a higher proportion of the effective, constraint-seeking questions relative to the other question types, and that the number of constraint-seeking questions was correlated with children's accuracy in guessing the identity of the card hidden in the special box. Legare et al. (2013) interpret these results as evidence that children can use questions to solve problems in a efficient manner. Converging evidence in support of this interpretation comes from experimental work using this approach finding that children prefer to direct questions to someone who is knowledgeable compared to someone who is inaccurate or ignorant (Mills, Legare, Bills, & Mejias, 2010; Mills, Legare, Grant, & Landrum, 2011),

Although the OED approach has provided a formal account of seemingly unconstrained information seeking, there are several ways in which it falls short as an explanation of human self-directed learning. Coenen et al. (2017) argue that in practice OED models make several critical assumptions about the learner and the problem, including the hypotheses/questions/answers under consideration, that people are actually engaging in some kind of expected utility computation in order to maximize the goal of knowledge acquisition, and that the learner has sufficient cognitive capacities to carry out the computations.

In the next section, I argue that limitations of the OED approach can be productively reconstrued as opportunities for understanding how learning from other people can scaffold self-directed learning. I focus on integrating social learning with five key components of the OED model: learners' inquiry goals, hypotheses, questions, answers, and stopping rules. The key insight is that learning from more knowledgable others provides the building blocks that are required for children to engage in effective self-directed learning.

Part III: Active learning within social contexts

Why should we attempt to integrate social and active learning accounts? First, children do not re-invent knowledge of the world, and while they can learn a tremendous amount from their own behaviors, much of their generalization and abstraction is shaped by input from other people. Moreover, social learning can sometimes be the only way to learn something and sometimes it can be a faster or more efficient route for learning. Finally, children are often surrounded by parents, other knowledgeable adults, and older peers – all of whom may know more about the world than they do, creating contexts where the opportunity for social learning is ubiquitous.

In addition, there is a body of empirical work showing that active learning can be biased and ineffective in systematic ways. For example, work by Klahr and Nigam (2004) showed that elementary school-aged children were less effective at discovering the principles of well-controlled experiments from their own self-directed learning, but were capaple of learning these principles from from direct instruction. D. B. Markant and Gureckis (2014) showed that active exploration provided no benefit over passive input in an abstract category learning task when there was a mismatch between the target concept and adults' prior hypotheses going into the learning task. And McCormack et al. (2016) found that 6-7 year-olds showed no learning benefits when allowed to actively intervene on a causal system compared to observing another person performing the interventions, which the authors suggest might be due to the relative decrease in cognitive demands in the observational learning condition.

In a comprehensive review of the self-directed learning literature, Gureckis and Markant (2012) point out that the quality of active exploration is linked to aspects of the learner's understanding of the task: if the representation is poor, then self-directed learning will be biased and ineffective. Coenen et al. (2017) go a step further and outline the challenges of demonstrating efficient active learning behaviors. Might social learning accounts have something to say in addressing the mixed results and challenges in the self-directed learning literature?

This section proposes one potential solution to the challenge of characterizing children's learning as efficient information seeking guided by OED principles. I take the OED model outlined in Coenen et al. (2017) as a starting point for defining efficient inquiry behavior, and use it to integrate social and active learning accounts. The benefit of this formal framework of self-directed learning is that it makes the different components of active learning explicit and highlights aspects that might be particularly challenging for young learners with limited cognitive resources.

I propose that we can reconstrue the "limitations" of the OED account as a model of human learning as opportunities for understanding how social contexts (i.e., interactions with more knowledable others) can support information seeking. In each section, I highlight the developmental challenge for each component of the OED model and then discuss how features of the social learning context could influence play a role. I also highlight prior work that highlight the potntial for social contexts to shape self-directed learning and point to interesting, open questions that are promising areas for future work.

Inquiry goals. An inquiry goal refers to the underlying motivation for people's information seeking behaviors. Often this is simply defined as a search for the correct hypothesis amongst a set of candidate hypotheses. Intuitively, an inquiry goal is what drives people to learn. Some examples of plausible inquiry goals that span across a variety of learning tasks and developmental research literatures include:

- Is this person a reliable source of information? (selective learning)
- What is this speaker referring to? (referential uncertainty)
- What types of objects are called "daxes"? (category learning)
- How does this toy work? (causal learning)
- Where should I look next? (allocation of visual attention)

Without an explicit inquiry goal, it becomes difficult for an active learner to compare the quality of different behaviors since the learner cannot evaluate how an action will lead to learning progress. Coenen et al. (2017) illustrate this point by highlighting how researchers often go to great lengths to communicate the specific inquiry goal of an experimental task, saying:

> "The importance of such goals is made clear by the fact that in experiments designed to evaluate OED principles, participants are usually instructed on the goal of a task and are often incentivized by some monetary reward tied to achieving participants that goal. Similarly, in developmental studies, children are often explicitly asked to answer certain questions, solve a particular problem, or choose between a set of actions." (p. 32-33)

Thus, characterizing children's goals during learning becomes critical for evaluating the quality of self-directed learning behaviors. However, this is no easy task since children could be considering a wide range of goals during any moment and there is no guarantee that learning progress should be one of the goals. In fact, one line of theorizing about OED as a model of human inquiry argues that we should only expect to see efficient information seeking behaviors in contexts where there is a clear task and learning goal. For example, when a parent gives their child a new toy with several buttons on it and the child's goal is to figure out how to make it work. In this case, we could ask whether the child approaches the learning task in an efficient way, selecting actions that are most likely to provide useful information about the toy's causal structure.

In the previous example, we see the potential for children's interactions with more knowledable others to play a role in triggering inquiry behavior. That is, adults and older peers have the capacity to construct contexts with clear learning goals in order to support children's own information seeking. This connection draws on influential ideas in cognitive development that frame social learning as a form of scaffolding where children are placed in contexts that present something new to be learned but importantly conatin learning goals that are achieveable given children's current capabilties (e.g., Zone of Proximal Development (Vygotsky, 1987), Rogoff's theory of Guided Participation (Rogoff et al., 1993), and more recently Guided Play (Weisberg, Hirsh-Pasek, & Golinkoff, 2013)).

For example, Weisberg et al. (2013) define guided play as an intermediate learning context that falls between totally unstructured free play and constrained direct instruction. The boundaries between these contexts are difficult to define, but the critical dimension is the level of control that the more knowledgable participant exerts over the activity. In free play, the child decides what to do next; whereas in direct instruction, the more knowledgable person explicitly tells the learner what to do, asks questions, or demonstrates new concepts.

In their review, they present the following example to illustrate the key difference between guided play and direct ins

> For example, a teacher with the goal of teaching new vocabulary words could take a direct instruction approach, by telling children the meanings of the new words they encounter in a storybook or by showing examples: "This is a helmet. A helmet goes on your head to stop your head from getting hurt if you fall off your bike." Or, she could take a guided-play approach, introducing the new words in the context of a child's play episode while encouraging children to think

> broadly about the word's meaning: "She's got a helmet on while riding her bike. What do you think would happen if she fell off her bike and wasn't wearing her helmet?" (p. 106)

While these contexts appear quite similar, the key difference is whether the child initiated the activity. Weisberg et al. (2013) hypothesize that guided play context provides the right combination of structure with the opportuntity for children's to exercise self-efficacy over learning, and leads to better learning outcomes.

One less-emphasized feature of the Guided Play proposal is the importance of an adult initializing a clear learning goal for the activity. In the previous example, if we removed the adult and only provided the child with a storybook to explore, it is unclear what goals the child would pursue when deciding what actions to take. However, the very presence of an adult who has knowledge of the names of objects in the book and has the goal to teach those names to the child changes the potential for the child to engage in informations-seeking behaviors. More formally, we can connect this example to the OED framework of self-directed learning, and it becomes clear that one potentially important role of more knowledable others is to present children with a clear learning goal, which in turn sets the stage for children to reason about what actions to take next (e.g., what question to ask or what object to point at) and how those actions might best support the current learning goal (i.e., learning the names of objects in the storybook).

Another interesting connection between social contexts and children's inquiry goals comes from a body of work exploring how children's input shapes their implicit theories of intelligence and in turn influences the goals they choose to pursuse in novel learning contexts (Dweck & Leggett, 1988). Specifically, implicit theories of intelligence refer to children's internal working models of the world and provide general frameworks for processing information and generating predictions about behavior. Dweck and Leggett (1988) propose a causal model where implicit theories of intelligence cause different goal orientations, which interact with perceptions of present ability to generate different behaviors. For example, if children hold a belief that intelligence is malleable (an incremental theory), they will want to increase competence (select a learning goal) and therefore be more likely to select tasks that support learning (mastery-oriented).

Empirical work has shown that children can be oriented toward learning goals by an experimenter. For example, Elliott and Dweck (1988) directly manipulated elementary school-aged children's goals by presenting them with a choice between one of two tasks described in the following ways:

- Performance task. In this box we have problems of different levels. Some are hard, some are easier. If you pick this box, although you won't learn new things, it will really show me what kids can do.
- Learning task. If you pick the task in this box, you'll probably learn a lot of new things. But you'll probably make a bunch of mistakes, get a little confused, maybe feel a little dumb at times — but eventually you'll learn some useful things.

Elliott and Dweck (1988) found that when children were oriented towards the learning goal, they tended to choose the more difficult "learning" task even though they were likely to make mistakes and risk looking incompetent. In another study, Dweck and Leggett (1988) showed that children who already held performance goals viewed effort on a task as an index of ability, whereas children with learning goals view effort as a means for improvement. Morever, both lab-based experiments and observational work provide evidence that the language adults choose to use when praising chidren can shape how likely children are to hold implicit theories that emphasize learning over and above performance goals (Cimpian, Arce, Markman, & Dweck, 2007; Gunderson et al., 2013).

Taken together, the research on implicit theories suggests another pathway through which social contexts can trigger inquiry goals. We can recast the Elliott and Dweck (1988) finding – that children oriented toward learning goals select harder tasks – in terms of the OED framwork. That is, the goal manipulation is an instance of the social context initializing an inquiry goal, which in turn influences children's decision making, leading children to select behaviors that result in a higher chance of learning new concepts, an explicit prediction that falls out of the OED model of human inquiry.

One important gap in the literature on inquiry goals is a good estimate of how often children participate in contexts with clear learning goals in their daily lives, as opposed to contexts where learning goals are absent or contexts where children are clearly pursuing other non-learning related goals (e.g., some example here). Moreover, there is a need for more research on the kinds of events that lead children to generate inquiry goals. However, Rogoff et al. (1993)'s work on *Guided participation* provides an interesting counter-example where they coded the rate of "caregiver orienting" behaviors in parent-child interactions with their 12- to 24-month-old infants across four different cultural communities (a Mayan Indian town in Guatemala, a middle-class urban group in the United States, a tribal village in India, and a middle-class urban neighborhood in Turkey) that varied along the dimensions of how separated children were from adult activities and whether formal schooling was emphasized. Specifically, caregiver orienting was defined as doing the following behavior during parent-child interaction around a set of novel toys,

> Caregiver orients child involved introducing new information or structure to the child (at any point in the episode) regarding the overall goals or a key part of the event or what was expected in the situation. Orienting framed a major goal, not just specific little directives for particular actions.

Rogoff et al. (1993) found that parents in all four communities produced high rates of structuring and orienting behaviors (with the lowest rate of structuring being 81% of play episodes). Thus, when placed in a structured activity, adults make sure children are aware of the goal (e.g., learning the function of the novel toy). However, the communities differed in how often children were directly involved with adult activities in day-to-day life, with the children raised in rural villages often having early acces to adult economic and social activities. An interesting open question is whether older peers and adults need to be directly engaging with the child in order to trigger inquiry goals and efficient self-directed learning behaviors. Perhaps increased access to observing lots of adult goal-directed behaviors can faciliate children to generate leanring goals, for example as they see activies being completed that they do not understand.

One important direction for future research to map the space of children's goals during everyday learning contexts. It would be interesting to know the proportion of children's daily activities that involve contexts where there is a clear learning goal either being demonstrated by the child or by older peers and adults. It would also be useful to know how the distribution of these tasks changes as a fnction of development, especially as children enter school and across different cultural contexts where children have differential access to structured (e.g., lessons and sports) vs. unstructured activies (e.g., free play).

Hypotheses. After establishing that there is something to be learned, the next key component of inquiry is deciding what hypotheses should be considered and tested. Intuitively, a hypothesis is a candidate explanation about how the world works. For example, if a child is in a concrete word learning context – i.e., she hears a new word ("dax") and is surrounded by a three unfamiliar objects (A, B, and C) – then she might entertain at least[4] the following hypotheses about the meaning of dax: dax = A, dax = B, or dax = C.

The set of hypotheses under consideration is critical for measuring effective self-directed learning. The usefulness function outlined in Part II works by comparing the learner's uncertainty over hypotheses before and after the she performs some action on the world. Without knowing what is in the hypothesis space, it becomes challenging to figure out the best action for reducing uncertainty. Put another way, the OED framework does not easily deal with situations where learners might have to consider a large space of hypotheses, might actually hold the wrong hypotheses, or perform actions without considering any hypotheses at all. This scenarios seem plausible for young learners and thus present a challenge to using OED principles as a model of early active leanring.

However, one important functions of social learning contexts is to provide a clear set of

[4]This hypothesis space only considers one-to-one mappings.

possible explanations for the true state of the world. That is, adults and older peers, who might have access to the correct hypothesis, can restrict the hypothesis space in order to help guide children information seeking behaviors. The effect of social contexts on hypotheses parallels the effect on goals reviewed in the previous section: that the behaviors of other people have the capacity to initialize and constrain.

One relevant case study of the capacity for social contexts to constrain hypotheses comes from work on children's early word learning. The challenge for the young word learner is that even the simplest of words, concrete nouns, are often used in complex contexts with multiple possible referents, which in turn have many conceptually natural properties that a speaker could talk about. This creates the potential for an (in principle) unlimited amount of hypotheses that children could consider for the meaning a novel word. Remarkably, word learning proceeds despite this massive uncertainty, with estimates of adult vocabularies ranging between 50,000 to 100,000 distinct words (P. Bloom, 2002).

It does not seem plausible for children to entertain all hypotheses about possible word-object links. But how might children constrain the hypotheses that they consider? One proposed solution is for word learners to only consider a single word-object hypothesis at a time (Medina, Snedeker, Trueswell, & Gleitman, 2011; Trueswell, Medina, Hafri, & Gleitman, 2013). That is, the child could make an initial guess about the meaning of a new word, and then only consider that guess until she receives sufficient evidence that her initial hypothesis was incorrect. If she seees sufficient counter-evidence, then she will switch to a new hypothesis that better matches the statistics in the input.[5] Another influential account of early word learning, inspired by basic associative learning principles, argues that children store more than a single hypothesis, suggesting that the hypothesis space is gradually reduced via the aggregation of word-object labels across multiple labeling events (Siskind,

[5]This "propose-but-verify" account parallels work by E. Bonawitz, Denison, Gopnik, and Griffiths (2014) in the domain of causal learning, which suggests that a "Win-Stay, Lose-Sample" algorithm (inspired by efficient sampling procedures in computer science) provides a better explanation of children's hypothesis testing behaviors compared to an algorithm that enumerates the entire hypothesis space.

1996; C. Yu & Smith, 2012b). Support for this experimental work has shown that both adults and young infants can use word-object co-occurrence statistics to learn word meaning from individually ambiguous naming events (Smith & Yu, 2008). Moreover, adults show evidence of being able to recall multiple word-object links from an initial naming event (Yurovsky & Frank, 2015).

The key difference between these proposals is how much information learners store in their hypothesis space. Understading the nature of the hypotheses that learners consider is critical for evaluating children's ability to seek information with respect to those hypotheses. Some of our own work provides direct evidence that the social context of language learning can modulate the content of the learner's hypothesis space (MacDonald, Yurovsky, & Frank, 2017). Inspired by ideas from Social-pragmatic theories of language acquisition that emphasize the importance of social cues for word learning (P. Bloom, 2002; Clark, 2009; Hollich et al., 2000), we showed adults a series of word learning contexts that varied in ambiguity depending on whether there was a useful social cue to reference (i.e., a gaze cue). We then measured learners' memory for alternative word-object links at different levels of attention and memory demands. Results showed that learners flexibly responded to the amount of ambiguity in the input, and as uncertainty increased, learners tended to store more word-object links. Morever, we found that learners stored representations with different levels of fidelity as a function of the reliability of the social cue and despite having the same amount of time to visually explore the objects during the initial labeling event.

These results suggest that the content of learners' hypothesis spaces changed as a function of the quality of the social learning context. Further suppport for this idea comes from experimental work showing that even children as young as 16 months prefer to map novel words to objects that are the target of a speaker's gaze and not their own (D. A. Baldwin, 1993), and analyses of naturalistic parent-child labeling events shows that young learners tended to retain labels that were accompanied by clear referential cues, which served to make a single object dominant in the visual field (C. Yu & Smith, 2012a). One important direction for future research is to measure the full causal pathway from variation in social learning contexts to the nature of children's hypothesis spaces and their information seeking behaviors. For example, it would be interesting to know whether learners' subsequent information seeking behaviors would be affected by social context manipulations like the ones used in our task.

Questions. Questions in the OED framework refer to the experiments that a scientist can conduct in order to gather information with respect to their hypotheses about the world. When we consider "questions" in human informaion seeking, it's important to note that "questions" can map onto a range of information seeking behaviors, such as verbal questions, pushing a button to figure out how a toy works, and decisions about where to look. In fact, the capacity to provide general principles to explain such a broad range of behaviors is one of the strengths of the OED account as a model of human active learning.

The challenge for the young learner is to discover what behaviors are available and of those behaviors which might be particularly good for gathering information to support learning. In this section, I illustrate how the social learning context provides the input to this learning process via demonstrations of the range of actions that learners could take and by adults' modeling effective information seeking behaviors.

It seems obvious that children would look to older peers or adults to learn what actions are possible and useful. However, a large body of empirical work suggests that even young infants will not imitate every action that they see. Instead, children show evidence of "rational imitation" and look for cues about other people's goal-directed behaviors and use this information to determine what behaviors are worth imitating . For example, Gergely, Bekkering, and Király (2002) measured how often 14-month-old infants imitated an adult's inefficient action – turning on a light with her head (less efficient) instead of her hands (more efficient) – as a function of whether there was a relevant explanation for selecting the less efficient action (whether the adult's hands were occupied). They found a large difference in imitation rates across conditions (69% in the hands-free vs. 21% in the hands-occupied), suggesting that children recognized the reason for the inefficient action and chose to ignore the means and focus on the goal of turning on the light in the most efficient way possible.

The high rates of imitation in the hands-free condition highlight another important compoenent of learning from others' actions: that children tend to overimitate behaviors even when these actions are not directly relevant to the task. For example, Call, Carpenter, and Tomasello (2005) compared imitation behaviors of 2-year-old children after they watched someone demonstrate how to open a tube using only the necessary actions or using the actions and a style component that was unrelated to opening the tube (e.g., removing the tube's cap with an exaggerated twisting motion). Children imitated the causally irrelevant action at a high rate (93% of children), providing evidence that they were focused on reproducing each of the experimenter's actions and not just reproducing the outcome of opening the tube.

Other empirical work provides insight into the importance of considering the social factors that influence whether children choose to imitate. Carpenter, Akhtar, and Tomasello (1998) showed that 14- and 18-month-olds were less likely to imitate adults' action if the action was accompanied by a verbal cue that flagged the action as a mistake (e.g., "Whoops!"). Buchsbaum, Gopnik, Griffiths, and Shafto (2011) provide evidence that the children are more likely to overimitate when the adult is described as a "knowledgeable" teacher as oppossed to "naive." And Carpenter, Call, and Tomasello (2002) showed that giving children explicit information about another person's goals prior to a causal demonstration leads to an increase in imitation and learning of the correct casual structure.

Taken together, the work on children's learning via imitiation and their tendency to overimitate suggests that inferences about others' intentions plays a critical role in the actions that children will use in their own behaviors. For the purpose of this paper, this work provides a way forward for understanding the origin of the information seeking behaviors that might be available to children, i.e., what are the available actions that a learner could take to gather information.

One domain where progress has been made in understanding how social contexts directly shape children's information seeking capacities is verbal question asking. Consider that in order to ask a useful question in natural language, children must possess the requisite language skills, which are learned from their language input. Both experimental work and corpus analyses provide evidence that children's question-asking becomes more varied and effective over the first years of life (e.g., see Chouinard et al. (2007) and Legare et al. (2013) reviewed in Part II). Moreover, children improve in the timing of their turn-taking during question-answer exchanges, reducing the length of gaps between turns (Casillas, 2014). Interestingly, (**???**) also found that adults appeared to be sensitive to children's developing question-answering skills by asking more difficult questions (i.e., questions that required more complex answers) as children to older children and by modifying questions that appeared to confuse children (e.g., "Who is this? What's he called? Who is he? What is his name?"). It is interesting to consider how children might internalize these modifications as part of their own question asking behaviors.

The majority of the work on children's question asking has focused on aspects of the child's behavior, exploring how the type, content, and effectiveness of questions changes as children develop. However, several studies have measured aspects of caregivers question asking. For example, B. Yu Yue (2017) coded parent-child interactions from the CHILDES database to measure the amount of "pedagogical" questions in children's input. They differentiate "information seeking" questions from "pedagogical" questions, by coding whether the adult already knew the answer (e.g., "What's that called?"";"What does this button do?" vs. "What did you do at school?"), and interpreted the goal of the pedagogical questions as helping the child learn. Results showed that approximately 30% of parents' questions were pedagogical, 60% were information seeking, and 10% were rhetorical (i.e., not intended to be answered verbally). Parents also directed a smaller proportion of pedagogical questions to older children.

More experimental work linking adults' question-asking practices to children's behaviors is needed. This is especially interesing since observational studies have found that that parents' use of wh-questions predicts children's later vocabulary and verbal reasoning outcomes (Rowe, Leech, & Cabrera, 2017) and children of parents who were trained to ask "good" questions during bookreading episodes at home also asked better questions during bookreading sessions at school (Birbili & Karagiorgou, 2009). One explanation for these associations is that wh-questions challenge children to produce more complex verbal responses that in turn builds verbal abilities. However, another interesting possibilty is that the frequency and type of questions that parents ask serve as models that could shape children's information seeking abilities by providing templates for useful behaviors.

Generating a set of questions represents the first step in efficient information seeking. Next, children have to evaluate the relative "goodness" (i.e., utility) of different behaviors. But how do children learn the features of a good question? One solution is to observe other people's question asking, recognize which questions are useful, and imitate those behaviors.

In fact, there is evidence from work with adults that shows a large difference between people's question-generating (harder) and question-evaluation (easier) skills. For example, Rothe, Lake, and Gureckis (2015) asked a group of adults to play a modified version of the game "Battleship" where they had to find the location of three ships that considted of 2-4 tiles and could oriented in either the vertical or horizontal direction on a 6x6 grid. Participants gathering information sequentially by uncovering one tile at a time. At different points in the task, the game would stop and participants were given the opportunity to ask any question using natural language. Rothe et al. (2015) used a formal model of the expected information gain of each question (i.e., the expected reduction in uncertainty after getting the answer) to evaluate the quality of adults' free-form questions. Results showed that people rarely produced high information value questions. However, in a follow-up experiment Rothe et al. (2015) had a different group of adults play the same game, but this time they provided the list of questions generated by participantsin the free-form version, and in this contexts, adults were quite good at selecting high information value questions.

Developmental work provides evidence of the same generation-recognition asymmetry. First, experimental work has shown that children younger than the age of three have difficulty generating appropriate verbal questions compared to their older peers in "Twenty Questions" task designed to measure question-asking skill (Mills et al., 2010, 2011). However, when Mills, Danovitch, Grant, and Elashi (2012) tested 3- to 5-year-old's capacity to learn from observing third-party question-answer exchanges. They found that even the youngest children were capable of using information elicited by others' yes/no questions to identify the contents of a box. Interestingly, children differentiated the usefulness of others' question-answer exchanges, paying more attention to them as compared to exchanges of irrelevant information.

Together, these results suggest that even at an age where generating questions "from scratch" might be difficult, children can observe and learn from questions that occur in their social environment. Mills et al. (2011) also explored this phenomenon by directly manipulating whether children were exposed to a training phase where adults modeled effective questions prior to playing the question asking game. They found that even though children were not successful at constructing good questions on their own, they were able to ask effective questions at much higher rate following explicit modeling.

Work with elementary-school-aged children in the domain of scientific inquiry also shows that generating a good question is a challenging aspect of inquiry skills. One particular relevant example come from Kuhn and Pease (2008)'s 3-year intervention study that compared children who were directly trained on inquiry skills (e.g., understanding the objectives of inquiry and identifying questions) to a group of slightly older students who had not participated in the training. Children in the training group showed progress in the skills, but children in the comparison group failed to develop these skills in the absence of the particular kinds of input. Summarizing one of the key results,

> Consistent with the findings of Kuhn and Dean (2005), identifying a question appears to play a key role in making the rest of the inquiry cycle productive. In

the probabilistic version of Ocean Voyage in year 2, for example, students floundered until they were helped to formulate a specific research question. Like other components of the inquiry process, this skill is not one a student learns once and has mastered.

A final example of how social contexts change the set of possible questions is the very fact of having other people around adds a social "target" for information seeking behaviors. This is in contrast to the effects of social context discussed until this point that serve as inputs that shape subsequent information seeking behaviors. Intuitively, if a child is trying to learn how a toy works, they could try actions to test the system directly (i.e., seek information directly from the world). But if another perosn is present, then they can choose to ask questions or seek help via noverbal means (i.e., seek information directly from another person). Thus, the very presence of another person modifies the choices that are available to the learner.

Recent empirical work has begun to explore the factors that affect children's decisions about whether to seek information from the world or from other people. For example, (**???**) had 4- to 6-year-old children decide how toto learn about a novel social category: "moozles." The concept was either visible (e.g., the color of hair) or invisible (e.g., an internal preference). Children were given a choice of looking directly at the moozle or asking a moozle expert. Six-year-olds chose to look for a visible property and to ask for an invisible property above chance in both experiments; whereas four-year-olds behavior was a bit noisier but showed a preference for the rational looking behavior with additional cueing in a follow-up experiment.

Other relevant examples comes from work on children's help-seeking behavior. (**???**) had children build toys that required multiple steps, and on each each step children were given the opportunity to ask for help from the experimenter. Each step varied in difficulty and children naturally varied in their toy building skill. Children asked for help when the step was harder, and less competent children asked for help more often, suggesting that preschoolers sought help in a systematic way – when they needed it and not when they didn't. Moreover, work by (**???**) found that 16-month-old infants are selective in help-seeking, turning to a social target to seek information or acting directly on the world depending on which information source ws more likely to help them reach their current goal. In this case, the infants' goal was to make a malfunctioning toy produce music and the critical manipulation was whether children saw evidence that explained the likely cause of failure being the toy versus their capacity for making the toy play music. When the toy was likely to be broken, they reached for a new object (queried the world), but in contrast, when the evidence suggested that the child was the issue, then they sought help from a nearby adult.

Some of our own work has explored how the presence of another person might change the dynamics of children's decisions about where to look during familiar language comprehension.

In sum, the set of questions that children consider provide the tools in their information seeking toolkit. However, we need more research to understand how children generate possible questions. One possible explanation explored in this section is that children might use their powerful imitiative learning skills to model the question-asking behaviors demonstrated by more knowlegable others present in their. Moreover, social contexts fundamentally change the set of behaviors that are available to the developing learner by providing a social target for information seeking behaviors.

Answers. Answers in the OED model refer to

- I think the pedagogical inference work fits in here. We get more information out of answers that we know were selected with our learning as the goal.

- Selective learning literature also fits in here since reasoning about the expertise of another person might change the amount of belief updating that occurs from a certain answer. When we are selective with whom we ask for information, we are using their past behavior at generating answers to our queries and using that to guide our future question asking. Thus, the role of the people in the self-directed learning context matters for the calculus. Put another way, not all information sources are created equal.

Note that there's an interesting distinction between active learning behaviors that directly affect social targets (or are directed towards social targets) such as questions and social referencing compared to active learning behaviors that might be changed by the presence of a social partner or being in a communicative context such as gaze patterns to explore the visual world or motor behaviors to explore a new toy.

Stopping rules.

- Case study 1: luke and ellen's work on persistence in pedagogcial contexts
- Case study 2: hyo and liz's work no exploration in pedagogical contexts.
- "That said, new research on the development of questioning indicates that preschoolers can some- times determine when they have gathered sufficient information to address their questions (e.g., Frazier, Gelman, & Wellman, 2009; Kemler Nelson, Egan, & Holt, 2004)." (mills)

Conclusions and a way forward

Models of self-directed learning should include information the social-communicative context in which learning often occurs. Reasoning about other people modulate the choices that learners make: whether it's who to talk to, what to look at, or what questions to ask. Moreover, models of social learning should take into account the choice behaviors available to the learner. i.e., think about teaching as reasoning about another person's active learning or setting up a social learning context where the learner selects actions

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Table 1

How active and social learning affect basic learning processes with relevant citations.

Type of learning	Change in learning process	
Social	Enhanced attention and memory	The presence of social partners makes
Social	Better information	Social partners tune input to learner's
Social	More restrictive Inferences and generalization	Psychological reasoning leads to stron
Active	Enhanced memory	Active behaviors engage a range of ba
Active	Better information	Learner have access to prior knowledg
Active	Less restrictive inferences and generalization	In these cases, self-directed learners m

Table 2

How features of social learning contexts map onto different components of the OED account.

OED model component	Description	
Inquiry goals	targets of information seeking behaviors. "What should I learn?"	Where do
Hypotheses	beliefs about the world. "this toy is a dax"	Where do
Questions	actions that gather information about hypotheses. "Is that a dax?"	How to g
Answers	outcomes that occur in response to questions. "yes, that's a dax."	How to fi
Stopping rules	decisions to stop collecting information	How to k