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How attention and working memory work together in the pursuit of goals: The development of the sampling-remembering trade-off

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A B S T R A C T

Most work in the last 50 years on visual working memory and attention has used a classic psychophysical setup: participants are instructed to attend to, or remember, a set of items. This setup sidesteps the role of cognitive control; effort is maximal, tasks are simple, and strategies are limited. While this approach has yielded important insights, it provides no clear path toward an integrative theory (Kristjánsson & Draschkow, 2021) and, like studying a town's walkability by having its college students run the 50-yard dash, it runs the danger of focusing on edge cases. Here, in this theoretical opinion article, we argue for an approach where dynamic relationships between the agent and the environment are understood functionally, in light of an agent's goals. This means a shift in emphasis from the performance of the mechanisms underlying a narrow task ("remember these items!") to their control in pursuit of a naturalistic goal ("make a sandwich!", Land & Hayhoe, 2001). Here, we highlight the sampling-remembering trade-off between exploiting goal-relevant information in the environment versus maintaining it in working memory. We present a dynamic feedback model of this trade-off – where the individual weighs the subjective costs of accessing external information versus those of maintaining it in memory – using insights from existing cognitive control models based on economic principles (Kool & Botvinick, 2018). This trade-off is particularly interesting in children, as the optimal use of internal resources is even more crucial when limited. Our model makes some specific predictions for future research: 1) an individual child strikes a preferred balance between the effort to attend to goal-relevant information in the environment versus the effort to maintain it in working memory, 2) in order to maintain this balance as underlying memory and cognitive control mechanisms improve with age, the child will have to increasingly shift toward remembering, and 3) older children will show greater adaptability to changing task demands.

Introduction

Open up nearly any cognitive psychology textbook. The chapter on attention will start with the quote by William James that attention is "taking possession by the mind, in clear and vivid form" (p. 404. James, 1890), then likely goes on to describe models by Broadbent, Posner, Sperling, and Treisman, leading up to more recent work by Wolfe, Nobre, and Simons. Then, the chapter on working memory will likely begin with Baddeley describing a system "that provides temporary storage and manipulation of the

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information necessary for… complex cognitive tasks" (his work (Baddeley, 1992) has been cited more than a quarter million times), followed by Cowan's theory (Cowan, 1988, 1999; Cowan et al., 2021) and then, if focusing on *visual* working memory, we would find summaries of research by Luck, Vogel, Alvarez, and Brady.

This division reflects the fact that most empirical research on visual attention and working memory in the past century has approached these constructs separately. This separation, ironically, stems from an attempt to measure each without the influence of the other: maximizing attention when measuring memory, and minimizing memory demands when measuring attention. This is an attempt to create ideal conditions – well-informed, motivated participants doing simple, tasks – to isolate best-case performance (we have contributed to this literature by measuring working memory capacity in infants and toddlers, see, Blaser & Kaldy, 2010; Cheng et al., 2020; Kaldy & Leslie, 2003, 2005). This, however, generates a challenge for generalization: real-world conditions are not ideal, performance is rarely best-case, and attention and memory are always in interplay outside the lab. While this approach has yielded important insights, it provides no clear path toward an integrative theory (Kristjánsson & Draschkow, 2021; Van der Stigchel, 2020) and, like studying a town's walkability by having its college students run the 50-yard dash, it runs the danger of focusing on edge cases.

In spite of this historical division, there have been studies of attention and memory within a common framework. One influential example is Cowan's 'Focus of Attention' and the embedded processing model (Cowan, 1988, 1999; Cowan et al., 2021), and work by Engle, Kane, and colleagues (Engle et al., 1999; Kane et al., 2001) based, in part, on the covariation of individual differences in tests of visual attention and working memory. Chun and colleagues' framework is another representative example (Chun, 2011; Chun et al., 2011) where attention may be turned outward to information in the environment, or inward, toward one's own internal representations. And, while the past twenty years have seen some other approaches (Gazzaley & Nobre, 2012; Kiyonaga & Egner, 2013; Lavie et al., 2004) linking *sampling* (via visual attention and eye movements) to *remembering* (keeping information active and allowing for its manipulation), there has been relatively little work explicitly addressing *what governs* their interplay during the pursuit of a goal. Here, we propose that the interplay of attention and working memory can only be understood in light of knowing an agent's *goals* – similarly to how Gibson claimed that visual perception can only be understood in light of knowing what vision *is for* and considering the environment as part of the problem to be understood (Gibson 1979; Richardson et al. 2008). And, where the interplay of sampling versus remembering is governed by the balancing of a common currency, *cost.* This means a shift in emphasis from how a target mechanism *performs* ("Remember all the cued items!") to how mechanisms are *controlled* in pursuit of a naturalistic goal ("Make a sandwich!" (see e.g., Land & Hayhoe, 2001).

In short, we argue that developmental science should treat *cognitive control* as a central explanandum, characterized in the context of goal-driven, naturalistic tasks, and incorporate novel, formal models (Badre, 2022; Steinbeis, 2023). *Cognitive control* is the set of processes or capacities that together drive adaptive, goal-directed mental processing (Badre, 2022; Badre & Nee, 2018; Botvinick et al., 2001; Egner, 2017), and its study goes back to Atkinson and Shiffrin's classic work on the control of memory systems (Atkinson & Shiffrin, 1968). The deployment of cognitive control typically involves the selection of a mental operation and the monitoring of its progress. The selection processes are based on cost-benefit computations (see, e.g., Chater & Oaksford, 1999; Lieder & Griffiths, 2019). Recent cognitive control models have put *cognitive effort* at the center of these cost-benefit computations (Agrawal et al., 2022; Inzlicht et al., 2018; Kool et al., 2017; Kool & Botvinick, 2018; Shenhav et al., 2017; Westbrook & Braver, 2015). According to the highly influential *Expected Value of Control* model (Shenhav et al., 2013, 2017), we determine how much cognitive effort to exert by weighing the costs and benefits of allocating cognitive control to various processes, including working memory maintenance (Westbrook et al., 2013), and then choose the one with the highest expected value. (We think it can help connect different segments of the literature here by identifying that 'cognitive effort' here largely overlaps with the construct that working memory researchers refer to as 'internal resources' or simply 'resources'; see, e.g. Barrouillet et al., 2004, 2011; Doherty et al., 2019; Superbia-Guimarães & Cowan, 2023).

However, the cognitive control literature has mainly focused on modeling situations where all the problem-solving and associated costs are confined to the observer's head. In this theoretical opinion article and in our related empirical work, we attempt to connect the cost-benefit heuristics of the cognitive control literature to what we call (based on Somai et al., 2020) the *sampling-remembering trade-off*: "When it's up to you, how much will you remember?". Our model can be applied to questions about the trade-off in general and as it applies to children, where working memory and cognitive control capabilities are still developing.

The sampling-remembering trade-off

The seminal work of Mary Hayhoe and Dana Ballard, starting in the'90 s, first explicitly addressed the question of how sampling (attention, and eye and hand movements) and remembering (visual working memory) are integrated in naturalistic situations while pursuing a goal (Ballard et al., 1995; Hayhoe et al., 1998; Hayhoe & Ballard, 2005). In one study, they had participants copy a model by picking up (with a mouse) a set of building blocks and assemble them in a separate workspace, while eye and mouse movements were monitored. "Subjects choose not to operate at the maximum capacity of short-term memory *but instead seek to minimize its use* [emphasis added]" (Ballard et al., 1995). Given the opportunity to refer back to the model, participants *took it* instead of attempting to encode and maintain the entire model in memory and assembling it in one go. (Even in tasks without a memory component, like categorization, participants may prefer sampling strategies that reduce cognitive effort over ones that, say, maximize information gain, see Meier & Blair, 2013.) This work led some to characterize people as 'cognitive misers', meaning that we avoid exerting cognitive effort (here, to maintain information in working memory) by relying on external resources (Kool et al., 2010; Risko et al., 2014; Taylor, 1981). But the story is more complicated than that.

If there is sufficient 'cost' to access an external source: physical effort, for instance moving one's head or eyes (Ballard et al., 1995; Hayhoe et al., 1998; Inamdar & Pomplun, 2003; Kristjánsson & Draschkow, 2021) or a time delay (Hardiess & Mallot, 2015; Inamdar & Pomplun, 2003; Kibbe & Kowler, 2011; Sahakian et al., 2023; Somai et al., 2020), or the task itself logically requires noting relationships between multiple items, for instance finding sets (Kenderla & Kibbe, 2023; Kibbe & Kowler, 2011) or solving geometry problems (Epelboim & Suppes, 2001), participants *will* remember more. In another line of research that started in the 70′s that focused on the role of knowledge and expertise in memory, participants were asked to reconstruct briefly presented chess positions on a board (Chase & Simon, 1973; Gobet & Simon, 1998). Beyond the classic demonstration that chunks are functional units in our mind, these studies also showed that participants at all skill levels memorized less when the task was to copy the position, with opportunities to revisit it, than when they only had one chance to memorize the board (Gobet & Clarkson, 2004). (Expert chess players are not just more efficient at coding information, but in sampling it in the first place, with faster, more strategic scanning of board positions, see Charness et al., 2001). Thus, the finding that adults reduce (but not necessarily minimize) their cognitive effort to encode items in their working memory whenever possible has been well established.

Finally, a third robust related line of research has emerged in the last ten years: the study of *cognitive offloading*, e.g., tilting one's head to read a rotated map, creating a physical reminder, or sharing information with another person. (For the first review laying the foundations, see Risko & Gilbert, 2016, for empirical studies, see e.g., Armitage et al., 2020; Armitage & Redshaw, 2022; Dunn & Risko, 2016; Gilbert et al., 2020; Grinschgl et al., 2021; Hu et al., 2019; Storm & Stone, 2015). Indeed, our propensity to seamlessly integrate information that is outside our heads with our own knowledge is the basis of one of the most influential philosophical ideas of the last 25 years, the *Extended Mind hypothesis* (Clark, 1999; Clark & Chalmers, 1998); an especially relevant framework as we increasingly use technology (phones, internet, AI tools) as extensions of our mind.

These findings match intuitions from everyday goals, like assembling an Ikea bookcase from the assembly diagram: we *trade off* the use of external resources (looking back at the assembly diagram) with the use of internal resources (maintaining assembly information in working memory) depending on how accessible the diagram is, or how scatterbrained one feels. Our view, motivated below in the context of our model, is that an individual trades off sampling versus remembering in order to strike – given the context and incentives of a particular goal and their own abilities – a *preferred balance* between the *subjective costs* of using external resources (time investment, physical movement) with the *subjective costs* of using internal resources (the cognitive effort required to maintain and manipulate goal-relevant information in working memory). Changes in the costs to access external or internal sources, then, would upset this balance, and the individual will use the sampling-remembering trade-off, like the reestablishment of homeostasis, to regain balance. During development, then, as the cost to use internal resources effectively decreases (given the maturation of underlying memory and cognitive control systems) the child must continually rebalance, applying some of this newfound facility in a shift toward more remembering.

A gap in our understanding

One of the primary reasons to exploit external resources is to reduce cognitive effort (Hayhoe & Ballard, 2005; Risko & Gilbert, 2016), but this requires recognizing the demands of one's goals, and one's strategies for reaching them. The ability to monitor and control one's cognitive effort (Niebaum et al., 2019; Niebaum & Munakata, 2020; O'Leary & Sloutsky, 2017), and the ability to perceive cognitive effort as costly (Chevalier, 2018; Ganesan & Steinbeis, 2022) gradually emerge during early childhood. 5–8 years of age seems to be the most important period in this regard. Shifts in the use of external resources require monitoring the effort needed to use working memory (Kelly & Risko, 2022), and children's ability to identify, or opt for, an 'easier' task (Niebaum et al., 2019, 2021; Niebaum & Munakata, 2020; O'Leary & Sloutsky, 2017) or use external resources selectively based on the difficulty of a task (Armitage et al., 2020; Bulley et al., 2020) is *beginning* to emerge around 5 years of age. For instance, 6-year-olds, but not 4–5-year-olds, will, similarly to the Risko et al. study (2014) with adults, physically rotate a paper map as opposed to engaging in mental rotation (Armitage & Redshaw, 2022). In addition, this is the age range where children are gaining metacognitive access to their subjective uncertainty (Baer et al., 2018; Vo et al., 2014) and where the child's developing working memory abilities begin to be guided explicitly (Ahmed et al., 2022; Forsberg et al., 2021; Spanoudis et al., 2015). We will return to the role of metacognition in the sampling-remembering trade-off later on.

Achieving a goal requires integrating the sampling of goal-related information from the environment with the manipulation of internal representations, and understanding the optimal management of resources is even more crucial when those resources are more limited and their control is still developing (Persaud et al., 2020). This means the lack of attention to the sampling-remembering tradeoff in children leaves a significant gap in our understanding. For instance, children's steadily increasing working memory capacity across childhood (Ahmed et al., 2022; Davidson et al., 2006; Tulsky et al., 2014) provides a unique opportunity to test predictions – for instance, linking individual differences in the sampling-remembering trade-off (see Hardiess & Mallot, 2015, for similar work in adults) to individual developmental trajectories in working memory – that could not be tested in adults. It is important to note here that the question of what are the mechanisms underlying working memory development, particularly, age-related improvements in both short-term storage and processing, have been studied extensively for more than a half-century (for reviews, see Cowan, 2016, 2022). A recent version of Cowan's influential developmental model posits that as children's knowledge of the world grows, they get better at offloading items from their focus of attention to activated long-term memory, and that this is one of the central processes underlying working memory development (Superbia-Guimarães & Cowan, 2023; see also Rhodes & Cowan, 2018). The question of how activated long-term memory can play a role in the sampling-remembering trade-off in children, to the best of our knowledge, has not gotten much attention. We think there are many interesting questions that could be raised, for example, when children prioritize offloading to activated long-term memory over cognitive offloading to external resources.

There have been only a few studies directly addressing the sampling-remembering trade-off in children. Haselen et al. (2000) and Hoffman et al. (2003) used a model-copying paradigm similar to Hayhoe and Ballard's (1995) and found that 5–12-year-old children showed similar eye movement patterns as adults, however, memory usage was not measured (and their sample sizes were relatively small, between 8 and 11). In a recent study, Kenderla and Kibbe (2023), following on the work of Kibbe and Kowler (2011) with adults, found that 8–10-year-old children adapted their visual search strategies depending on the accessibility of external resources. In their task, which combines elements of the card games *Set* and *Memory*, children were asked to find a set of three cards that satisfied a logical rule. The cards depicted abstract objects that differed along four featural dimensions (color, shape, pattern, and marker placement). They were shown face-down and could be exposed with a click; access cost was manipulated by varying the delay between the click and the exposure. In the simplest rule condition, children had to find three cards that shared one feature (there were two other conditions, with increased rule complexity). This required maintaining multiple features of visited cards, choosing a feature to use for the search, then sampling cards until three matching cards were found and potentially revising the chosen feature as cards were exposed. The authors found that children relied more on external resources – that is, they re-sampled cards more often before making their final selections – when the cards were more easily accessible (children also tended to sample more when faced with more complex matching rules). Our empirical work, which we turn to in the next section, builds on these results, using a streamlined task that isolates working memory maintenance costs and can be tailored for younger children.

Balancing sampling versus remembering

Imagine a child helping their parent in a store. The parent shows a long shopping list to the child (conveniently, with pictures of to-be-purchased items) so they can run off and grab items from the shelves. In this scenario, the list itself is an *external resource* the child may use, while the child's own working memory is an *internal resource*; successful shopping will involve managing both. There are inherent incentives – implicit and explicit motivators and rewards from the context and parent – for the child to pursue this goal. Then too, for each resource, there are associated *use costs*. For instance, to return to the parent to look at the list there is the associated time commitment and physical exertion. Then, to maintain a subset of list items in working memory, there is the associated cognitive effort, which is driven in part by the amount and duration for which information needs to be maintained. The relative levels of these two costs (is the parent all the way across the store or right next to the child? Can remembered information be utilized quickly or only after some protracted period? How much can the child reliably remember?) will affect how the child trades off sampling the list versus remembering its contents.

To capture this dynamic interplay,we developed a simple feedback model from which some concrete predictions can be made (Fig. 1**)**. Our model combines existing research on the sampling-remembering trade-off (Ballard et al., 1995; Draschkow et al., 2021; Kibbe & Kowler, 2011; Liang et al., in press; Somai et al., 2020) with current insights from the cognitive control literature about effort (Kool & Botvinick, 2018; Shenhav et al., 2017; Westbrook et al., 2019) and focuses on just one aspect of strategic sensorimotor decision making (e.g., Wolpert & Landy, 2012): the *dynamic regulation of the trade-off* between internal and external resource use. For any given goal with its incentives and rewards, the individual gravitates to a preferred balance of subjective internal and external use costs. (This is analogous to the homeostasis mechanisms that underlie, say, osmoregulation, where eating a salty snack encourages fluid intake (reducing salt concentration) and drinking a lot of water encourages salt intake (decreasing the relative amount of fluids)). Then, any increase in external use costs encourages the individual to trade off for internal resource use (remembering more; sampling less), thereby driving down subjective external use costs *but also* increasing subjective internal use costs, keeping their use in check. Of course, too, any increase in internal use costs encourages a trade-off for external resource use (remembering less; sampling more) thereby driving down those costs *but also* increasing subjective external use costs, keeping their use in check.

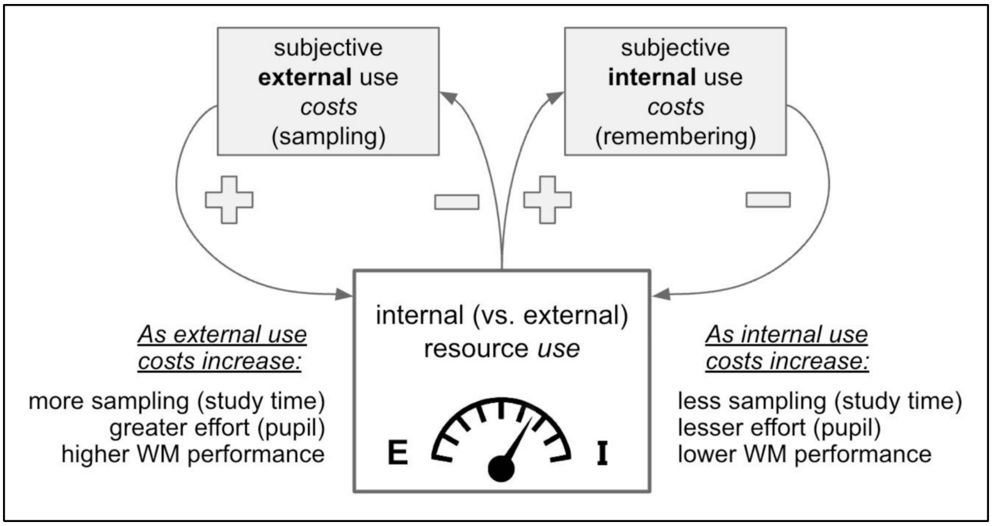

Fig. 1. A model of the sampling-remembering trade-off. A child trades off sampling for remembering to maintain a preferred balance between the subjective costs of using external resources (e.g., additional time; physical movement) versus internal resources (e.g., the cognitive effort to maintain information in working memory). In our Shopping Game paradigm, we parametrically vary internal use costs and external use costs.

This model produces some straightforward predictions. For instance, sticking to our shopping analogy, adding an annoying, goal-delaying *lag time* before one can access the shopping list increases external resource use costs. The desire to reduce this cost would encourage the participant to make fewer trips. To accomplish that means *remembering more on each visit to the shelves*. Behaviorally, this would be observed as an increase in 'study time' (the time the individual chooses to spend encoding list items), a concomitant increase in cognitive effort (as indexed by the task-evoked pupil response, see Beatty, 1982; Hess & Polt, 1964; Kahneman & Beatty, 1966; Mathôt et al., 2018), better working memory performance (more items remembered per trip), and, of course, fewer trips. In short, remembering more; sampling less. By enacting this trade-off from external resource reliance toward greater internal resource reliance, a (*worthwhile*) increase in internal use costs is incurred, and the cost introduced by the lag is offset, as the individual returns to a preferred balance of the two. On the other hand, if one were to selectively increase just internal use costs (say, by making the information less reliably available; see the next section for an example), the opposite set of predictions would hold – less remembering; more sampling – as the individual strives to reestablish their preferred balance. One interesting prediction of this model is that if one were to introduce a time delay during *memory maintenance* (see the next section for an example), this would increase *both* internal use costs (given the greater cognitive effort required for the extended maintenance) *and* external use costs (again, by imposing an annoying potential slowdown in reaching one's goal). In this case, in spite of introducing a cost increase identical in nature and quantity to our previous scenarios, we may see them partially cancel out, resulting in little change in behavior at all, as the individual's *balance* of costs may not have been significantly perturbed.

Notably, this model does not require the specification of any new developmental processes, *per se*, in order to make developmental predictions. Instead, it offers predictions that are simply the consequence of rebalancing given the gradual development of working memory and cognitive control systems (Ahmed et al., 2022; Davidson et al., 2006; Diamond, 2013; Gathercole et al., 2004). At any given point in development, for a particular goal, the child strikes a preferred balance between subjective external and internal use costs. Then, as memory capacity and cognitive control skills increase over development, this effectively offers a reduction in internal use costs (i.e., less effort to remember the same amount), producing an imbalance if the child were not to adapt. So, with age, children will opt to remember a bit more (thereby, fortuitously, also offsetting some external use costs) in order to restore balance; like an increasingly chilly adult adding layers over the years to maintain body temperature. Consequently then as well, in the face of some change in task demands (a change in external access costs, say), older children – by virtue of having increased memory and increased cognitive control with which to deploy it effectively – will be better able to maintain balance. Put together then, over development, we should observe older children remembering more and sampling less, and showing greater adaptability to changing task demands.

The shopping Game: A flexible paradigm to study the sampling-remembering trade-off

We developed a child-friendly naturalistic paradigm to test our hypotheses, the "Shopping Game" (Liang et al., in press). The elements and the goal of shopping as an activity is a highly familiar script for children and can easily be turned into a game, as it was recognized by Z. Istomina in a study first published in 1948; republished in English in 1975 (Istomina, 1975; see also Schneider & Hasselhorn, 1994; Bertrand & Camos, 2015). Our paradigm uses a streamlined task that isolates working memory and is appropriate for younger children. Being able to test younger children is of utmost importance, as we discussed above since the cognitive control literature identifies 5–6 years of age as a plausible age of emergence for the trade-off. As far as we know, this was the first formal study of how external memory costs affect working memory use in children under 8 years of age.

The Shopping Game is played on a touch-screen tablet (see Fig. 2). As in the scenarios discussed above, participants were asked to select several items from a store based on a shopping list. Critically, the store and the list were not visible on the screen simultaneously, but children could toggle between them by tapping an icon. There was no time limit on the task, and children were told that they were allowed to go back to the list as many times as they wanted. Correctly selected items were crossed off on the 10-item list (to make it clear that they did not need to be selected again). As motivation, every correct selection in the store was rewarded with a star and accompanied by a pleasant sound, while every incorrect selection resulted in losing a star and an unpleasant sound.

One cost to use the external resource of the list comes from the time it takes the child to make a trip from the store's shelves back to the shopping list. As this *lag time* lengthens the child is increasingly likely to prefer making fewer trips, opting to trade off sampling in favor of remembering. (And vice versa, if lag time were *decreased.*) What keeps this process in check is the countervailing increase in

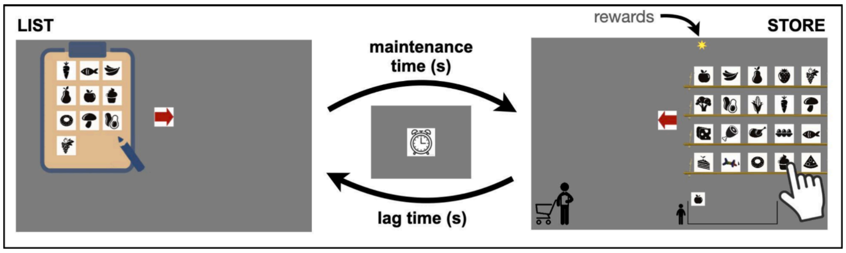

Fig. 2. "Shopping Game". The children's goal is to select items on the shopping list from the store. Importantly, the list and the store are not shown simultaneously. The child may toggle between the two by touching an icon. Each correct pick is rewarded with a star, and each false alarm results in losing a star. Various manipulations are possible to manipulate the *cost* associated with using the external resource of the list (e.g., varying *lag time*) and the internal resource of one's own working memory (e.g., varying memory *maintenance time*).

internal use cost that would come from the greater effort required to remember more items over time. In our first study with the Shopping Game, we manipulated lag time (Liang et al., in press). In a series of three preregistered experiments, we found that 5–8-year-old children were able to trade off sampling versus remembering, and, consistent with our model, we found that as external use costs increased (greater lag time), children *re-balanced*: 1) they made fewer trips to the list, 2) they tried to remember more items (increased *study time* of to-be-remembered list items), and 3) correctly selected more items more per trip. We have also found that even the younger, 5–6-year-old children explicitly recognized the effort costs and, when asked, the majority of them reported that the shorter-lag condition was easier. Importantly, metacognitive awareness of the relative difficulty was not related to children's trade-off ability; explicit recognition of the cost differentials was not needed for the trade-off.

In another study, we increased *internal* use costs by altering how 'reliably available' the information on the list was (Liang et al., 2025). Here, children were led to believe that the list might suddenly disappear (i.e., appear blank instead of showing the shopping list icons) at some hard-to-predict point during each trial. This cost – the prospect of performing poorly by relying on a glitchy list – should encourage children to remember more and sample less. Consistent with our predictions, we found that children relied less on the shopping list – referring back to it less often and for a longer period, and remembering more items – when they perceived the list as unreliable (and vice versa, making more, briefer trips to the list, and remembering less, when it was perceived as reliably available). Then, in a third study (with adults) we also manipulated *maintenance time* (Koolhaas et al., 2025). Here, an increase in the time to transition from the list to the store means both an increase in internal use costs (more effort to maintain remembered information over a longer period) *and* external use costs (an annoying slowdown for each use of the list). Our model specifies that an individual strives for a preferred balance of these costs, predicting that they may partially cancel out in this condition, resulting in little change in behavior. The pattern of results we observed is consistent with this prediction.

Future directions and implications

Attention and memory have been typically studied separately in laboratory settings, using paradigms where either attention is maximized while measuring memory performance, or memory demands are minimized while measuring attentional performance. Such studies (including those from our own lab, see Blaser & Kaldy, 2010; Hamilton et al., 2024; Kaldy & Leslie, 2005), while informative, could be considered degenerate cases. There have been many prominent calls for "wilding" cognitive neuroscience (Ibanez, 2022; Maguire, 2022; Nastase et al., 2020; Sonkusare et al., 2019), including developmental cognitive neuroscience (Hartley, 2022; Wass & Goupil, 2022). We see our work here as benefitting from these efforts: in keeping with the ubiquitous interplay of attention and memory in everyday contexts, we center the role of cognitive control, where an individual can, adaptively, *trade-off* sampling versus remembering. Through examining an individual's pursuit of a naturalistic goal, attention and memory are re-integrated.

Schooling as cognitive control training

How to motivate children to try their best (that is, exert more cognitive effort) has been the focus of extensive study in educational psychology. Dweck's influential work on the growth mindset (Dweck, 1986, 2006; Yeager & Dweck, 2012) is taught to parents, teachers, and, increasingly, children across the world. However, the study of the development of children's cognitive effort deployment from a resource-rational analysis perspective (Lieder & Griffiths, 2019) only began a few years ago (Chevalier, 2018; Hadley et al., 2019; Niebaum et al., 2019; Steinbeis, 2023). In our recent empirical work, we focused on young, 5–6-year-old children (Liang et al., in press, 2025).

Besides there being no prior work on cost-dependent strategies in children at this early age, we were also driven by an interest in understanding the mechanisms underlying the "5-to-7-year shift", which refers to the period around school entry when children first formally face cognitive tasks that require memorization (Haith & Sameroff, 1996). This is a period of remarkable improvements in children's cognitive and self-regulation skills (Brod et al., 2017; Kim et al., 2020; Morrison et al., 2019). In fact, our recent *meta*-analysis of 27 experiments including more than 1,700 participants, has shown that the first year of schooling adds a small-to-moderate boost to working memory capacity beyond age-related maturation (Donenfeld et al., under review). Whether we can see the schooling effect (or any other training effects) influencing the sampling-remembering trade-off remains an interesting question for future study.

Summary and future work on the sampling-remembering tradeoff

Most work on the sampling-remembering tradeoff up to this point has only manipulated external use costs (but see the rule complexity manipulation in Kibbe & Kowler, 2011; Kenderla & Kibbe, 2023). Our innovative Shopping Game paradigm allows us to independently manipulate both internal and external use costs and investigate the predictions of this feedback model in both children and adults. The most notable contributions of our approach are: 1) it targets working memory while holding variables such as task type and complexity constant, 2) it specifies *what is being traded-off*, i.e. the 'common currency' of *cost,* and 3) it centers an individual child's attempt to maintain a *preferred balance* of these costs.

In ongoing and future studies, we are examining children's effort expenditures using neurophysiological measures, such as pupillometry (Eckstein et al., 2017; Kaldy & Blaser, 2020), as has been done in working memory tasks with infants in our lab (Cheng et al., 2019) and in paradigms similar to ours in adults (Koevoet et al., 2024). Pupillometry can provide a more direct measure of effort expenditure during encoding than study time alone, as well as a direct measure of cognitive effort during maintenance in each trip.

As described above, the heart of our model is *dynamic regulation*: as changing task demands and/or internal states modulate the subjective costs to use external versus internal resources, the system will adjust the trade-off to *compensate* in an effort to reestablish a preferred balance. Implicit here is the fact that these balance points – the *ratio* of internal to external costs – may be an idiosyncratic, but stable, preference of an individual child. Future research may attempt to determine sampling-remembering *developmental trajectories* and their link to cognitive control and working memory maturation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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