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# Reasoning More Efficiently with Primary Knowledge Despite Extraneous Cognitive Load

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## Abstract

Geary's evolutionary approach in educational psychology differentiates between primary (low cognitive costs and motivational advantage) and secondary knowledge (high cognitive costs and no motivational benefit). Although these features have been well demonstrated in previous work, the underlying mechanisms remain unclear. To investigate it, in a reasoning task, the present study varies (i) the content of the problems (primary knowledge vs. secondary; e.g., food vs. grammar rules), (ii) the intrinsic cognitive load (conflict or non-conflict syllogism, the former requiring more cognitive resources to be properly processed than the latter) and (iii) the extraneous cognitive load (via a Dot Memory Task with three modalities: low, medium and high cognitive load). Analyses assessed the influence of these variables on performance, problem solving speed and perceived cognitive load. Results confirmed the positive impact of primary knowledge on efficiency, particularly when intrinsic cognitive load was high. Surprisingly, the extraneous cognitive load did not influence the performance in secondary knowledge content but that in primary knowledge content: the higher the additional load was, the better the performance was, only for primary knowledge and especially for syllogisms with high intrinsic load. Findings support evolutionary theory as secondary knowledge would overload cognitive resources, preventing participants from allocating sufficient resources to solve problems. Primary knowledge would allow participants to process the additional load and to increase their performance despite this. This study also raises the hypothesis that a minimum cognitive load is necessary for participants to be invested in the task.

## Keywords

primary/secondary knowledge, cognitive load theory, desirable difficulties, reasoning

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## Introduction

### *Acquiring Primary Knowledge and Learning Secondary Knowledge*

Evolutionary psychology has demonstrated that contemporary human beings exhibit superior cognitive performance when dealing with ancient knowledge characterized by high adaptive value, encompassing domains such as food, movement, animals, and diseases (e.g., Bonin et al., 2019; Fernandes et al., 2017; Nairne, 2016), compared to more recent knowledge domains, including logical reasoning, mathematics, health prevention behaviors and explicit grammar rules. This phenomenon has been observed in diverse cognitive functions, namely memory (Nairne, 2010), decision making (Sparks et al., 2018), reasoning (Lespiau & Tricot, 2018), and learning (Paas & Sweller, 2012). For example, the principle of adaptive memory (Nairne, 2010) emphasizes that our memory systems have evolved to recall information related to our survival.

Thus, the content of the information to be memorized influences the retrieval of that information: individuals remember information related to animate objects (e.g., predators) more efficiently than information related to inanimate objects (e.g., furniture) (Leding, 2018).

According to the evolutionary approach to knowledge acquisition (Geary, 2007, 2008; Geary & Berch, 2015, 2016), the cognitive architecture of our species has evolved to favor the assimilation and retention of specific knowledge types termed

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“biologically primary knowledge” or simply primary knowledge henceforth. This knowledge would be directly useful for our adaptation and would concern folk psychology (e.g., self-awareness, face recognition, facial expressions, speech, group dynamics, theory of mind), folk biology (e.g., fauna, flora, food) and folk physics (e.g., navigation, sense of time, tool use). Its acquisition would be unconscious, rapid, effortless and conditioned by individual’s direct environment. We would also be particularly motivated to process it. For example, we are able to learn and speak our mother tongue fairly quickly, without conscious effort. We are also motivated to engage in activities that facilitate the elaboration of primary abilities and knowledge. For instance, species-typical parent-child interactions facilitate the elaboration of children’s language abilities and ensures they acquire the language of their parents.

However, humanity has an enormous capacity to create new knowledge, such as reading and mathematics. Our cognitive architecture could not have adapted to acquire recent knowledge unconsciously, rapidly nor without effort (Richerson & Boyd, 2005; Youssef et al., 2012). Consequently, this so-called “new” biologically secondary knowledge is characterized by long learning, demanding in effort and cognitive resources. People have domain-general cognitive abilities (e.g., working memory, top-down attentional control) that allows them to create and learn secondary knowledge. This knowledge would not be intrinsically motivating, so we would need an extraneous motivation to deal with it. For example, a foreign language acquired in adulthood is considered as a biologically secondary knowledge. Schooling, which has been in existence for 5000 years and was until recently accessible only to a limited portion of the population (Eskelson, 2020), serves as the primary method for acquiring this kind of knowledge.

We are able to speak our mother tongue without explaining how we acquired this skill (Paas & Sweller, 2012). Then we use this mother tongue to build new knowledge like writing and grammar rules or a second language. Primary knowledge is indeed considered as the basis for learning secondary knowledge. Their opposite characteristics are only the expression of a different cognitive processing due to evolution, but in the end, the distinction between these two types of knowledge is fuzzy (Tricot & Sweller, 2014). Recent studies attempted to use primary knowledge to facilitate the learning of secondary knowledge, in particular by reducing the impact of cognitive load on working memory (Castro-Alonso et al., 2015; Glenberg et al., 2011; Kirschner, Paas, & Kirschner, 2011; Kirschner, Paas, Kirschner, & Janssen, 2011; Mavilidi et al., 2015; Nokes-Malach et al., 2015; Paas & Sweller, 2012; Ping & Goldin-Meadow, 2010; Toumpaniari et al., 2015; Van Gog et al., 2009). Lespiau and Tricot (2022b) used more directly primary knowledge to facilitate the learning of secondary knowledge. They designed two versions of the same statistical exercises: a first version used content (surface) related to primary knowledge (e.g., “Consider the following hypothesis: *taking care of cats at an animal shelter* improves self-esteem. Characterize the different variables, calculate the correct test,

and validate or invalidate the hypothesis”); a second version used content (surface) related to secondary knowledge (e.g., “Consider the following hypothesis: *using the subjunctive mood in writing short stories* improves self-esteem. Characterize the different variables, calculate the correct test, and validate or invalidate the hypothesis”). The first version, using content (surface) related to primary knowledge improved university students’ performance and efficiency while maintaining their motivation (especially as this content was presented first). By contrast, secondary knowledge content had a negative effect on performance and seemed to reduce motivation when presented first. The beneficial effect of primary knowledge likely resulted from the reduced working memory demands of processing this surface content (in the statistical exercise) and an inherent interest in this content (Sweller, 2016; Sweller & Sweller, 2006).

### *Processing Information and Managing Cognitive Loads*

Our cognitive architecture is at least composed of (i) long-term memory with unlimited capacity as information storage and (ii) working memory with limited capacity (Sweller, 2004). Faced with new knowledge, the information we can process is limited by the working memory capacity (Cowan, 2010; Miller, 1956; Paas & Ayres, 2014). This limited capacity is adaptive and forces the individual to focus on the elements that make sense regarding the situation rather than dealing with an infinite number of possibilities in the problem space (Sweller, 2004, 2016; Sweller & Sweller, 2006).

Nevertheless, it is an important constraint, particularly in the context of learning. Cognitive load theory predicted decrements in learning and performance when the task overloads the individual’s working memory capacity (Sweller et al., 2011). This approach defines three types of cognitive load: the intrinsic one related to the interactivity of elements in the task (Kirschner, Paas & Kirschner, 2011; Paas et al., 2003; e.g., for a French learner, the intrinsic load associated with learning irregular verbs in English is lower than that of learning a text in English), the germane one related to learning (e.g., to learn new concepts from a text on chemistry, a learner need to integrate the new information and link it to the previous knowledge in long-term memory) and the extraneous one related to the elements not useful to the task but which must be treated at the same time (Choi et al., 2014; e.g., the presentation format of a learning material: for a math exercise involving calculating the hypotenuse of a right-angled triangle, a strong extraneous load could be to visually separate the figure from the measurement elements).

Intrinsic cognitive load and extraneous cognitive load are assumed to be additive and form cognitive load. Depending on this load, the remaining cognitive resources handle the integration of the intrinsic cognitive load to enable learning (i.e., germane processing; intrinsic and germane cognitive load are closely linked, Paas & van Merriënboer, 2020). The task should be designed such that most of the learners’ working memory and attentional resources are ideally focused on the most germane parts of the task. If an individual’s cognitive

resources are exceeded, task performance is reduced, as well as their learning. Central to the theory is to balance the three loads so that learning can occur efficiently. For example, according to the task and the learner's profile, to promote learning, it is necessary to minimize cognitive load so that cognitive resources can be directed towards processing intrinsic cognitive load and thus germane cognitive load (Chen et al., 2016; Ginns, 2006; Kalyuga et al., 2003; Sweller et al., 2011). However, reducing task difficulty and cognitive load does not automatically lead to improved learning due to potential expertise reversal effects (Kalyuga et al., 2003) or desirable difficulties (Bjork & Kroll, 2015). Decreasing cognitive load is efficient when designing learning materials and tasks only when overall cognitive load is too high. If learners have high prior knowledge and it makes the task too easy, reducing cognitive load even further can impede learning. In such conditions increasing the difficulty of the materials and/or task demands in a relevant way is more efficient (Bjork & Bjork, 2020).

The limited working memory constrains the learning of new information. Until recently, this limited capacity was supposed to apply to the acquisition of all kinds of information (Paas & Sweller, 2012). However, as our cognitive system has evolved to easily and quickly process primary knowledge, the cost in working memory is minimized for this type of information (Geary & Berch, 2015). But most approaches do not differentiate the types of knowledge involved (Sweller, 2008). Indeed, the problem is that our cognitive architecture has not evolved to learn the massive secondary knowledge that we are asked to assimilate. When we are faced with secondary knowledge, we have neither the motivation nor the abilities (inspired by genetics) to assimilate it automatically. Thus, cognitive load theory applies only to secondary knowledge (Sweller, 2008), if we consider that certain primary knowledge domains can transition into secondary knowledge categories when acquired at a later stage in life. This transformation is exemplified by instances such as second-language acquisition in adulthood (Roussel et al., 2017) or the development of facial emotion recognition skills in individuals with autism spectrum disorder (Wieckowski et al., 2020).

### *Reasoning Tasks as a Way of Varying Cognitive Loads*

The question of cognitive load and of the consumption of cognitive resources is an important element in research on reasoning, particularly in the dual-process approach (Evans, 2003, 2016). Information can be processed through two different types of mechanisms. Types 1 are fast, automatic processes that are not limited by working memory capacity. They are systematically implemented and are responsible for individuals' first response to a problem of formal logic. Types 2 are slower. They are implemented only when a conflict is detected between two responses (even unconscious, De Neys, 2012; De Neys et al., 2008; De Neys et al., 2010; De Neys et al., 2011; De Neys & Glumicic, 2008; Kahneman & Frederick, 2005), subject

to first response inhibition (De Neys & Franssens, 2009) and sufficient resources available in working memory to generate type 2 response (De Neys & Bonnefon, 2013). So, when faced with a syllogism as follows:

*All cakes can be eaten,  
Chocolate cookies can be eaten,  
Therefore chocolate cookies are cakes.*

The first answer that comes to mind is to say that the conclusion is valid because of the belief heuristic. Cognitive resources must be engaged to detect the conflict associated with this first response, inhibit it and produce the new response contrary to our beliefs that the conclusion is invalid. This type of problem is considered as a conflict one because the logical status of the conclusion conflicts with previous beliefs/knowledge (e.g., when the conclusion is believable but logically invalid as in the example, or incredible and valid). Problems which the validity of the conclusion is consistent with its believability are considered as non-conflict. Compared to non-conflict problems, conflict problems, in addition to a poorer performance (De Neys, 2006), lead to longer response times (De Neys & Glumicic, 2008; Handley & Trippas, 2015) and individuals appear to have less confidence in their responses (De Neys & Feremans, 2013; Johnson et al., 2016). These belief biases are accentuated when an additional task overloads cognitive resources without leaving enough to process the main problem (e.g., Dot Memory Task, Bethell-Fox & Shepard, 1988; De Neys, 2006; Miyake et al., 2001; Trémolière et al., 2017).

Reasoning with syllogisms is therefore a good methodological framework to investigate the influence of different cognitive loads (intrinsic with the type of problem conflict/non-conflict and extraneous with the addition of a task not related to the problem) on secondary knowledge (i.e., logical reasoning). Indeed, the classical normative logic is secondary knowledge because we did not evolve to be logical (Stanovich et al., 2011), we learn to be effective most of the time even if it does not meet the normative standards (Geary & Bjorklund, 2000). In addition, logical problems offer the advantage of being adaptable to various contents with ease by modifying the terms used (Cosmides & Tooby, 2004; Griggs & Cox, 1982). Recent studies actually used logical reasoning tasks to test the evolutionary approach to knowledge by varying the content of the problems: related to primary knowledge (e.g., with food or animals' characteristics) or to secondary knowledge (e.g., with mathematics and grammar rules) (Lespiau & Tricot, 2018, 2019, 2022a). Whether the content was fictional or real, data consistently showed that content related to primary knowledge increased performance, emotional and cognitive investment and decreased perceived cognitive load. Despite supporting Geary's evolutionary theory, the precise mechanisms underlying the obtained results remain not entirely elucidated.

## Present Study

In order to pursue and complete previous work, this paper seeks to provide a better understanding of the mechanisms involved in the processing of the evolutionary defined knowledge types by varying two types of cognitive load: the intrinsic one and the extraneous one. To this aim, participants were faced with syllogisms involving primary knowledge content (food, animals' characteristics) or secondary knowledge content (mathematics and grammar rules). Syllogisms could have a low intrinsic cognitive load (non-conflictual problems that can be solved by heuristics) or a high one (conflicting problems that require cognitive resources to be solved). In addition to this, we used a task whose three modalities gradually increase the extraneous cognitive load (Dot Memory Task). By definition (Geary & Berch, 2016), primary knowledge requires less cognitive resources thus is processed more quickly and easily compared with secondary knowledge. Therefore, problems with primary knowledge content should be processed more efficiently than those with secondary knowledge content. Moreover, problems with secondary knowledge content should be negatively influenced more by intrinsic and extraneous cognitive loads than those with primary knowledge content.

## Method

### Participants

Participants were 188 university students in France (45 men, 141 women, 2 others, mean age was  $20.1 \pm 4.9$ ), approached by University Facebook groups. Participants estimated their level in math at 42.9/100 ( $\pm 30.5$ ) and they liked logic games at 77.9/100 ( $\pm 23.9$ ).

### Materials

Each participant read the following instructions:

*We will now propose statements. These statements will be as follows:*

*"All things that have an engine need oil,*

*Cars have an engine,*

*Therefore cars need oil."*

*The premises (first two lines) must be considered as true.*

*The conclusion (last line) should only be accepted if it follows logically from the premises.*

*For each statement, you will have to judge whether or not the different conclusions proposed follow logically from their premises.*

We varied the syllogisms contents. Participants were faced either with sixteen syllogisms whose content was linked to primary knowledge (food or animals' characteristics) or with sixteen syllogisms whose content was linked to secondary knowledge (grammar or mathematics). Of the sixteen problems

presented to each participant, eight presented a conclusion whose logical status conflicted with its believability (conflict syllogisms) and eight presented a conclusion whose logical status was consistent with its believability. Each syllogism consisted of a universal affirmative first premise as well as a particular affirmative second premise and conclusion. Here are some examples of syllogisms used in the experiment (translated from French):

Primary knowledge contents (noted "K1" in results):

*All cakes can be eaten,*

*Chocolate cookies can be eaten,*

*Therefore chocolate cookies are cakes. (conflict: invalid logical status and believable conclusion).*

*All felines are wild animals,*

*Domestic cats are felines,*

*Therefore domestic cats are wild animals. (conflict: valid logical status and unbelievable conclusion).*

*All bitter-tasting, low-sugar fruits are yellow in color,*

*Bananas are yellow in color,*

*Therefore bananas are bitter-tasting, low-sugar fruits (non-conflict: invalid logical status and unbelievable conclusion).*

*All human beings have two eyes,*

*Women are human beings,*

*Therefore women have two eyes (non-conflict: valid logical status and believable conclusion).*

Secondary knowledge contents (noted "K2" in results):

*All French feminine adjectives end with -e,*

*"Jolie" ends with -e,*

*Therefore "jolie" is a French feminine adjective (conflict: invalid logical status and believable conclusion).*

*All prime numbers are odd numbers,*

*2 is a prime number,*

*Therefore 2 is an odd number (conflict: valid logical status and unbelievable conclusion).*

*All the French verbs of the first group end up with -er,*

*"Aller" ends up with -er,*

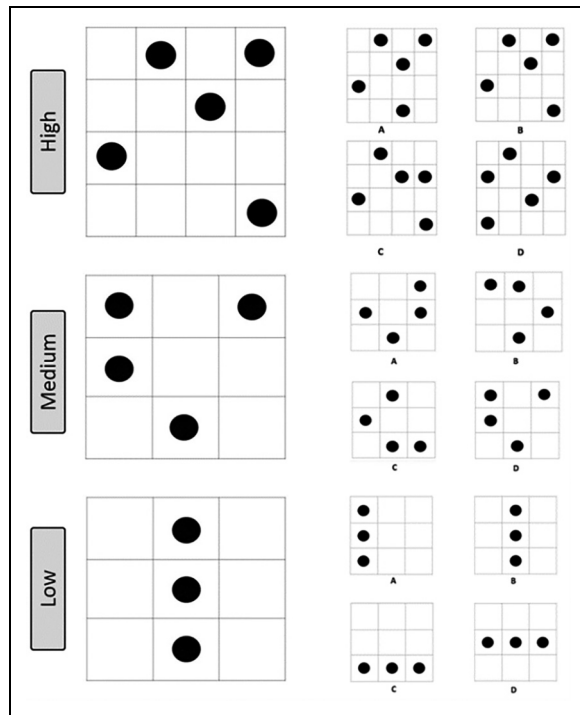
*Therefore "aller" is a French verb of the first group (non-conflict: invalid logical status and unbelievable conclusion).*

*All isosceles triangles have two sides of the same length,*

*Equilateral triangles are isosceles ones,*

*Therefore the equilateral triangles have two sides of the same length (non-conflict: valid logical status and believable conclusion).*

Participants respond to each syllogism by checking the box "the conclusion follows logically from the premises" or the box "the conclusion does not follow logically from the premises".



**Figure 1.** Examples of Dot Memory Task patterns regarding the three modalities of extraneous added cognitive load. Participants had to remember the pattern on the left and find it in the four proposals on the right.

The added cognitive load was manipulated between groups with a Dot Memory Task. Participants had to memorize a dot pattern more or less complex (high modality noted *CL high* in results: five dots pattern, medium modality noted *CL medium* in results: four dots pattern, low modality noted *CL low* in results: three aligned dots pattern) and recognize it among four proposals (Figure 1).

### Procedure

The experiment was conducted online with Qualtrics and 30 min long. First, participants had to memorize the position of several dots in a grid (according to their extraneous added cognitive load modality) displayed during 850 milliseconds. Then, they had to answer about the validity of four syllogisms at self-paced, presented on the same page, before finding which grid of dots was presented to them among four proposals (the aim of the Dot Memory Task was to load working memory while answering questions). The participants were confronted with 4 blocks according to this protocol, 16 syllogisms in total. Each block contained non-conflict or conflict syllogisms. The blocks were presented randomly. Of the participants, 95 worked on primary knowledge (added extraneous cognitive load: low = 31, medium = 32, high = 32) and 93 on secondary knowledge (added extraneous cognitive load: low = 31, medium = 32, high = 30). Feedback on performance in recognizing the grid was provided to the participants for each block

in order to ensure that they were giving this task sufficient attention and cognitive resources.

Performance was recorded in percentage of correct answers (regarding syllogisms and DMT). In addition, for each page and after completing four syllogisms, participants had to provide information on an analogic visual scale (from 0 to 100, they just move a cursor to the desired location on the scale): How much they (i) “enjoyed thinking about the questions” (emotional investment); How much they (ii) “wanted to find the correct answers” (cognitive investment/motivation); How much they were (iii) “confident about their given answers” (confidence); and How much they agreed with four sentences (iv) “the subjects were complex”, “you concentrated a lot to answer the four problems”, “memorizing the point grid was very easy for you” and “the whole exercise (4 syllogisms + dot grid) was very easy for you” (perceived cognitive load, Cronbach’s  $\alpha = .71$ ). The (v) speed (number of problems solved in one minute) to complete each page was also measured.

At the end of the experiment, a last page was added, similar to other syllogisms pages: it showed two syllogisms that take the form of the syllogisms used during the experiment but in a more abstract way by replacing the terms with ABC (“A is B, C is B, Therefore C is A” invalid and “A is B, C is A, Therefore C is B” valid) and two syllogisms not used in the study to assess far transfer abilities (“A is B, C is not B, Therefore C is not A” valid, “A is B, C is not A, Therefore C is not B” invalid). In the same way as in the main experimental task, performance and all variables were measured on this page. Then, in order to assess the overall cognitive load on the whole experiment, a question asked participants how well they agree with the proposals “the topics covered were complex”, “you concentrated a lot on this study” and “the study was very easy for you”.

Finally, participants responded to some personal information including their estimated level in math, their enthusiasm for solving logical problems and their feeling of having learned something during the experiment.

### Data Analyses

We anticipate that the participants will be more performant when faced with primary knowledge content than with secondary knowledge content, as the former is processed more easily. Secondary knowledge content should also be more impacted by the type of problem than primary knowledge content: the difference between non-conflict and conflict problems should be more important for secondary knowledge. Similarly, the added extraneous cognitive load should influence problems with secondary knowledge content, especially for conflicting problems (high saturation of cognitive resources).

A question allowed the participants to inform us that they made a break for more than 30 s during their run: 161 participants did not take a break, so we excluded the other 27 participants when the tested variable was speed. Linear mixed-effects models were used to analyze data. The Wald  $\chi^2$ , estimate and its Standard Error (*SE*) were reported for main analyses. We also

used between subjects' ANOVA (general influence of the added extraneous cognitive load) and contrast analysis (influence of the added cognitive load with regard to knowledge and problem types) as well as Tukey post-tests and chi-square test (influence of knowledge type on the feeling of learning). Means were noted  $M$  and standard deviation ( $\pm$ ). All variables were scaled for analyses and performed with R 3.3.2 and SPSS Statistics 20. Non-significant results were not presented unless otherwise specified.

## Results

### The Two Knowledge Types

Compared with secondary knowledge, primary knowledge elicited higher performance and speed (Table 1). The knowledge type did not significantly influence the performance for the last ABC test nor the other observed variables. However, the participants who faced primary knowledge during the experiment (41%  $n=39$ ) stated they reported more that they felt they had learned something than the participants who faced secondary knowledge (31%  $n=29$ ) ( $\chi^2(1)=3.55, p=.05$ ).

### The Influence of Syllogism Types on the Two Knowledge Types

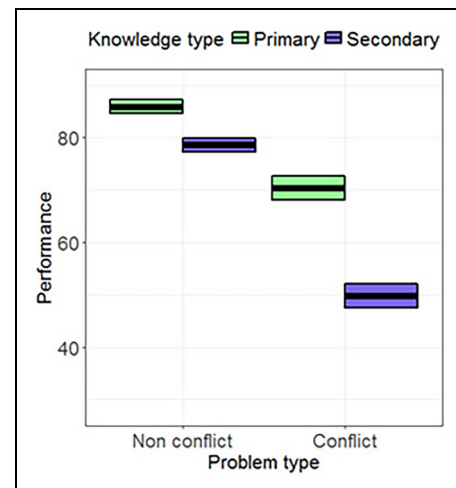
In accordance with literature, compared with conflict syllogisms, non-conflict syllogisms lead to higher performance ( $M_{non-conflict}=82.3 \pm 18.5$  vs.  $M_{conflict}=60.2 \pm 32.6$ ) ( $estimate = -0.77, SE = 0.07; \chi^2 = 108.80, p < .001$ ), higher confidence ( $M_{non-conflict}=59.9 \pm 27.0$  vs.  $M_{conflict}=55.2 \pm 26.8$ ) ( $estimate = -0.17, SE = 0.05; \chi^2 = 12.67, p < .001$ ) and lower perceived cognitive load ( $M_{non-conflict}=32.2 \pm 16.1$  vs.  $M_{conflict}=35.5 \pm 17.1$ ) ( $estimate = 0.19, SE = 0.05; \chi^2 = 14.81, p < .001$ ).

The interaction effect between the syllogism type and the knowledge type ( $\chi^2 = 10.26, p = .001$ ) (Figure 2) reflected a greater impact of the problem type on the performance for secondary knowledge ( $M_{non-conflict}=78.6 \pm 8.3$  vs.  $M_{conflict}=49.8 \pm 31.4$ , a score of 50 is considered to be at the level of chance) ( $estimate = 0.97, SE = 0.10; \chi^2 = 97.73, p < .001$ ) than on the performance for primary knowledge ( $M_{non-conflict}=85.9 \pm 17.9$  vs.  $M_{conflict}=70.3 \pm 30.6$ ) ( $estimate = 0.59, SE = 0.11;$

$\chi^2 = 28.03, p < .001$ ). Compared with secondary knowledge contents, primary knowledge contents always lead to higher scores whatever the problem type (non-conflict  $\chi^2 = 7.56, p = .006$ ; conflict  $\chi^2 = 20.55, p < .001$ ).

### Including the Influence of the Extraneous Cognitive Load

The extraneous added cognitive load influenced the performance on the Dot Memory Task ( $F(2,185) = 23.35, p < .001$ ;  $M_{CL\ low} = 93.9 \pm 10.7, M_{CL\ medium} = 90.2 \pm 15.1, M_{CL\ high} = 81.0 \pm 18.9$ , the high cognitive load modality significantly differ from the two other modalities,  $ps < .001$ , but the lower and the medium modalities did not significantly differ,  $p = .13$ ). It also influenced the perceived cognitive load throughout the experiment ( $\chi^2 = 5.47, p = .005$ ;  $M_{CL\ low} = 29.2 \pm 15.4, M_{CL\ medium} = 33.8 \pm 17.0, M_{CL\ high} = 38.5 \pm 16.4$ , the high cognitive load modality significantly differed from the two other modalities,  $ps < .05$ , the lower and the medium modalities differed marginally,  $p = .06$ ). The Dot Memory task performance was not significantly influenced by the

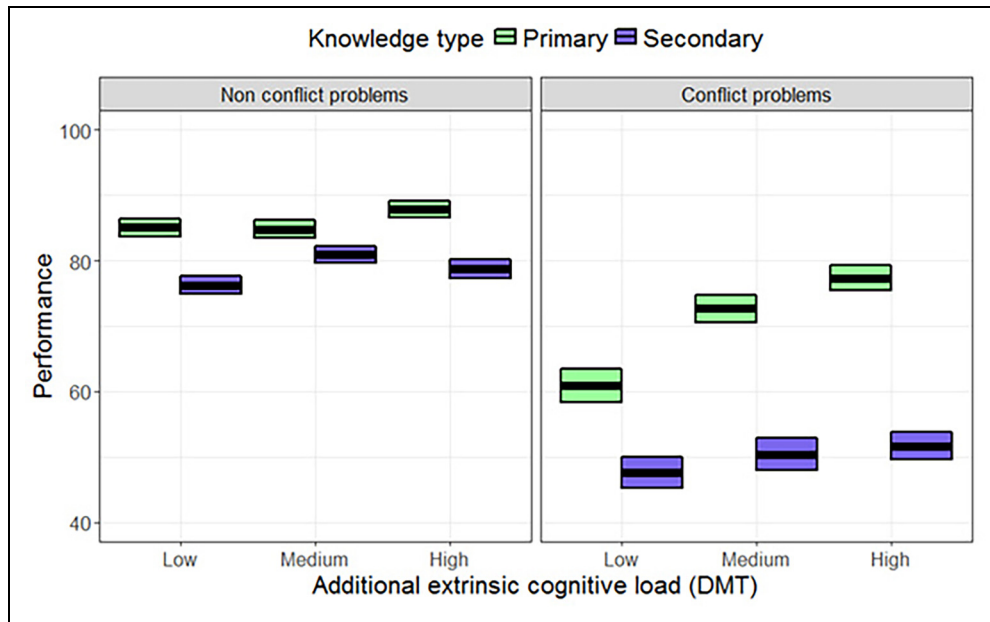


**Figure 2.** Interactions between the knowledge type and the problem type load on participants' performance (boxplots represent the mean and 95% of the confidence interval).

**Table 1.** Results From Linear Mixed-Effects Models Regarding the Influence of the Two Knowledge Types on the Dependent Variables.

	Primary knowledge		Secondary knowledge		Estimate	SE	$\chi^2$	$p$
	$M$	$SD$	$M$	$SD$				
Performance	78.1	26.2	64.2	29.4	-0.51	0.10	23.19	<.001
Enjoy answering questions	63.9	25.2	58.5	25.1	-0.21	0.14	2.20	.13
Want to find the correct answers	73.2	23.6	72.3	21.8	-0.06	0.14	0.19	.67
Confidence	59.8	26.9	55.3	26.9	-0.17	0.05	2.55	.11
Perceived cognitive load	33.8	17.0	33.9	16.4	0.04	0.13	0.11	.74
Speed (pb/min) ( $n = 161$ )	5.6	2.8	4.9	1.6	-0.28	0.13	4.95	.03

Note. Analysis are described with means ( $M$ ), standard deviation ( $SD$ ) and standard error of the estimate ( $SE$ ).



**Figure 3.** Interactions between the knowledge types, the problem types and the added extraneous cognitive load modalities on participants' performance (boxplots represent the mean and 95% of the confidence interval).

knowledge type presented nor the interaction of this latter with the extraneous added cognitive load type.

For primary content conflict problems, the extraneous added cognitive load had a significant effect on the performance ( $F(2,90) = 3.77, p = .03$ ). There was a significant linear trend ( $F(1,90) = 7.48, p = .008$ ) indicating that as the level of added cognitive load increased, performance increased proportionately. Planned contrast revealed that having a sufficient added cognitive load (medium or high) compared with having a low added cognitive load increased performance ( $t(90) = 2.51, p = .01$ ). Participants had a higher performance faced with a high added cognitive load compared with a low added cognitive load ( $t(90) = 2.73, p = .008; d = 0.70$ ). But a high added cognitive load did not increase performance compared with a medium added cognitive load ( $t(90) = 1.16, p = .25; d = 0.33$ ). Also, a medium added cognitive load did not increase performance compared with a low cognitive load ( $t(90) = 1.46, p = .15; d = 0.37$ ). The influence of the added cognitive load on the different problem (regarding their knowledge type content and their type of syllogisms conflict or non-conflict) as well as the contrasts were not significant for any other case than the one mentioned above (primary knowledge with non-conflict problems  $ps > .54$ , secondary knowledge with conflict problems  $ps > .61$  and secondary knowledge with non-conflict problems  $ps > .38$ ) (Figure 3).

## Discussion

This study sought to test the characteristics of the two knowledge types defined by the evolutionary approach. Primary abilities and knowledge are supported by evolved brain and cognitive systems that guide attention to primary domains and

support the effortless acquisition of the associated knowledge bases, such as one's native language. The acquisition of secondary knowledge, in contrast, is not supported by these evolved systems and thus their acquisition is dependent on domain-general abilities, such as working memory, and formal schooling. In order to test the impact of knowledge on cognitive resources, we varied the content of syllogisms (related to primary or secondary knowledge) and used two types of cognitive loads, one intrinsic (type of syllogism: conflict or non-conflict) and the other extraneous (Dot Memory Task with three modalities in order to investigate the evolution of the influence of the cognitive resources allocation for both knowledge types).

Results showed that participants exhibited greater efficiency when confronted with primary knowledge contents in comparison to secondary knowledge contents, especially when dealing with problems that demanded higher cognitive resources for their resolution. Surprisingly, the introduction of extraneous cognitive load did not have the anticipated detrimental impact on performance in secondary knowledge contents. Conversely, it had a positive effect on the performance in primary knowledge contents. Finally, these results are consistent with the evolutionary approach: secondary knowledge saturated cognitive resources and disengaged individuals, while low-cost primary knowledge enabled resources to be used to perform the additional task while reasoning. This study also raises the hypothesis that a minimum cognitive load is necessary for participants to be invested in the task.

The results of this study provide arguments in favor of the validity of the two knowledge types definitions given by evolutionary psychology (Geary & Berch, 2016). For the same level of motivation, confidence and cognitive load, participants are



thus more efficient in terms of performance and speed in reasoning about primary knowledge than secondary knowledge.

In addition, conflict problems required more cognitive resources to be processed (overall decrease in performance, confidence and increase in perceived cognitive load). Non-conflict problems did not require cognitive resources since heuristics are sufficient to solve them. Consequently, compared to a primary knowledge content, secondary knowledge content that require more cognitive resources were more sensitive to whether the syllogisms were conflict ones or not and was therefore negatively impacted by the intrinsic cognitive load.

Finally, the Dot Memory Task used in this experiment extraneously loaded cognitive resources effectively (influence on task performance and perceived cognitive load) and was not a priori abandoned to free up resources for answering syllogisms under difficult conditions (no significant influence of knowledge type). One would expect higher added cognitive load modalities to be deleterious especially for problems that require a lot of resources to be properly processed (conflict problems with secondary knowledge content). The results were surprising and did not follow the cognitive load theory. As expected, for non-conflict problems (whose resolution by heuristics was sufficient), the added cognitive load did not have any influence since these problems do not saturate the working memory and do not require any particular effort. Primary knowledge contents lead to higher performance because they further reduce cognitive load compared with secondary knowledge contents. Unexpected outcomes emerged for conflict problems that require more cognitive resources and investment to be processed. These conflict problems with secondary knowledge content seemed either (i) to overload cognitive resources and to not allow enough resources to deal with the problems or (ii) to undermine the motivation of participants who did not think they could succeed, generating cognitive conflict (Lespiau & Tricot, 2022a). Anyhow, performance was fairly close to random performance. Finally, it would appear that regardless of the source of cognitive load, as soon as secondary knowledge was involved, participants disinvested. However, when these conflict problems were presented with primary knowledge contents, the higher the added cognitive load was, the better the performance was. Since primary knowledge does not consume cognitive resources but conflict problems require investment, it would seem that cognitive load played a motivating role here for participants and allowed them to be wary of the answers given by heuristics. Thus, the added cognitive load only influenced cases where participants had to make an effort to solve problems (conflict syllogisms) and where the content leaves enough cognitive resources (primary knowledge). This is in line with evolutionary theory and with the characteristics of primary (low resource costs) and secondary (low motivation) knowledge.

The question remains as to why the problem type (intrinsic load) had an influence consistent with our hypotheses while the extraneous added cognitive load had an unexpected but theoretically correct effect. One explanation would depend on the internal or external nature of the task. Indeed, the problem type

is an internal difficulty to the task and might not be seen consciously by the participants whereas the Dot Memory Task is external to the task and its difficulty might be immediately understood. Unal et al. (2022) used a similar external load task in the context of math problem solving. They showed that the difficulty of the load task has a consistent influence on performance. The load task used here, as stated, probably was not very difficult for these participants. In the high added cognitive load or medium added cognitive load modalities, participants were able to perceive a challenge in addition to the reasoning task, which could have motivated them. The low added cognitive load condition could thus be perceived as not stimulating or even “debilitating”. This explanation is supported by the fact that participants in our sample rather liked logic games and potentially expected more challenge from this study. Thus, this protocol would benefit from being conducted again with people who do not like logic games or who do not spontaneously choose to participate in the experiment (e.g., with students in school time).

These results may be consistent with the cognitive load theory that also assumes that a minimum of load is necessary to enable learning. For example, in the case of material with low interactivity, the effect of the corrected example (which reduces the intrinsic cognitive load) is inconclusive, and it would be better to encourage learners to generate their own responses (Chen et al., 2016). Another study found that activities that require the most cognitive resources can have a significant positive effect on learning (Chi & Wylie, 2014). These activities, which are a priori more costly in terms of cognitive resources, could be related to primary mechanisms (e.g., social interactions in the generation process) (Geary & Berch, 2016). These results are also in line with the desirable difficulties approach: conditions that favor direct learning performance would not necessarily support long-term memory retention and transfer, while conditions that create a challenge would often optimize it (Bjork & Bjork, 2011). Ensuring that learners are confronted with the easiest possible learning conditions would therefore not always be enviable for the organization of knowledge in long-term memory (Bjork, 1994). On the contrary, the more difficult the material conditions, the deeper the treatment would be (Bjork, 2013; Bjork & Kroll, 2015; Fyfe & Rittle-Johnson, 2017; Rohrer et al., 2015). These desirable difficulties increase the cognitive load in working memory but would also generate a deeper information processing. However, if the learner does not have the necessary knowledge or skills to respond to these difficulties (saturation of working memory resources), they could become undesirable difficulties (Bjork & Bjork, 2011). In the present experiment, extraneous cognitive load could thus be used to motivate individuals to perform a task as long as it does not exceed working memory resources.

Another explanation for the results might be that the Dot Memory Task used was too simple since it was a recognition task and not a recall task. Nevertheless, this shows that too little added cognitive load could be deleterious. It would be interesting to replicate the experiment using a more complex

secondary task (e.g., add shapes instead of dots to the matrix and ask for shapes pattern recognition in addition to their position in the grid).

This study combines the framework of logical reasoning and different cognitive loads to assess the characteristics of the two types of knowledge defined by the evolutionary approach. To this end, participants had to solve syllogisms that could take different contents (primary vs. secondary knowledge) and intrinsic load (non-conflict or conflict problems). They were also faced with three modalities of extraneous cognitive load in order to observe the progressive impact of this load on the knowledge types. Results validated the non-costly aspect in cognitive resources of primary knowledge, so that it made it possible to manage several tasks at the same time, whereas secondary knowledge would generate a cognitive conflict. Findings also highlighted that a minimum cognitive load is needed to invest individuals in a task and that decreasing extraneous cognitive load is not necessarily the best idea.

### Declaration of Conflicting Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

### Ethical Approval

This study was conducted in accordance with the ethical standards of the institutional and national guidelines and with the Declaration of Helsinki (2008). Informed consent was obtained from all individual participants included in the study.

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### References

- Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(1), 12–23. <https://doi.org/10.1037/0096-1523.14.1.12>
- Bjork, E. L., & Bjork, R. A. (2011). Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning. In FABBS Foundation, M. A. Gernsbache, & J. R. Pomerantz (Eds.), *Psychology and the real world: Essays illustrating fundamental contributions to society* (pp. 56–64). Worth Publishers.
- Bjork, R. A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe & A. Shimamura (Eds.), *Metacognition: Knowing about knowing* (pp. 185–205). MIT Press.
- Bjork, R. A. (2013). Desirable difficulties perspective on learning. In H. Pashler (Ed.), *Encyclopedia of the mind* (pp. 134–146). Sage Publication.
- Bjork, R. A., & Bjork, E. L. (2020). Desirable difficulties in theory and practice. *Journal of Applied Research in Memory and Cognition*, *9*(4), 475–479. <https://doi.org/10.1016/j.jarmac.2020.09.003>
- Bjork, R. A., & Kroll, J. F. (2015). Desirable difficulties in vocabulary learning. *The American Journal of Psychology*, *128*(2), 241–252. <https://doi.org/10.5406/amerjpsyc.128.2.0241>
- Bonin, P., Thiebaut, G., Witt, A., & Méot, A. (2019). Contamination is “good” for your memory! Further evidence for the adaptive view of memory. *Evolutionary Psychological Science*, *5*, 300–316. <https://doi.org/10.1007/s40806-019-00188-y>
- Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). Animations showing Lego manipulative tasks: Three potential moderators of effectiveness. *Computers & Education*, *85*, 1–13. <https://doi.org/10.1016/j.compedu.2014.12.022>
- Chen, O., Kalyuga, S., & Sweller, J. (2016). Relations between the worked example and generation effects on immediate and delayed tests. *Learning and Instruction*, *45*, 20–30. <https://doi.org/10.1016/j.learninstruc.2016.06.007>
- Chi, M. T., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist*, *49*(4), 219–243. <https://doi.org/10.1080/00461520.2014.965823>
- Choi, H. H., Van Merriënboer, J. J., & Paas, F. (2014). Effects of the physical environment on cognitive load and learning: Towards a new model of cognitive load. *Educational Psychology Review*, *26*(2), 225–244. <https://doi.org/10.1007/s10648-014-9262-6>
- Cosmides, L., & Tooby, J. (2004). Knowing thyself: The evolutionary psychology of moral reasoning and moral sentiments. *The Ruffin Series of the Society for Business Ethics*, *4*, 93–128. <https://doi.org/10.5840/ruffinx200447>
- Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why? *Current Directions in Psychological Science*, *19*(1), 51–57. <https://doi.org/10.1177/0963721409359277>
- De Neys, W. (2006). Dual processing in reasoning: Two systems but one reasoner. *Psychological Science*, *17*(5), 428–433. <https://doi.org/10.1111/j.1467-9280.2006.01723.x>
- De Neys, W. (2012). Bias and conflict: A case for logical intuitions. *Perspectives on Psychological Science*, *7*(1), 28–38. <https://doi.org/10.1177/1745691611429354>
- De Neys, W., & Bonnefon, J. F. (2013). The ‘whys’ and ‘whens’ of individual differences in thinking biases. *Trends in Cognitive Sciences*, *17*(4), 172–178. <https://doi.org/10.1016/j.tics.2013.02.001>
- De Neys, W., Cromheeke, S., & Osman, M. (2011). Biased but in doubt: Conflict and decision confidence. *PLoS one*, *6*(1), e15954. <https://doi.org/10.1371/journal.pone.0015954>
- De Neys, W., & Feremans, V. (2013). Development of heuristic bias detection in elementary school. *Developmental Psychology*, *49*(2), 258–269. <https://doi.org/10.1037/a0028320>
- De Neys, W., & Franssens, S. (2009). Belief inhibition during thinking: Not always winning but at least taking part. *Cognition*, *113*(1), 45–61. <https://doi.org/10.1016/j.cognition.2009.07.009>
- De Neys, W., & Glumicic, T. (2008). Conflict monitoring in dual process theories of thinking. *Cognition*, *106*(3), 1248–1299. <https://doi.org/10.1016/j.cognition.2007.06.002>
- De Neys, W., Moyens, E., & Vansteenwegen, D. (2010). Feeling we’re biased: Autonomic arousal and reasoning conflict. *Cognitive*,

- Affective, & Behavioral Neuroscience*, 10(2), 208–216. <https://doi.org/10.3758/CABN.10.2.208>
- De Neys, W., Vartanian, O., & Goel, V. (2008). Smarter than we think: When our brains detect that we are biased. *Psychological Science*, 19(5), 483–489. <https://doi.org/10.1111/j.1467-9280.2008.02113.x>
- Eskelson, T. C. (2020). How and why formal education originated in the emergence of civilization. *Journal of Education and Learning*, 9(2), 29–47. <https://doi.org/10.5539/jel.v9n2p29>
- Evans, J. S. B. (2003). In two minds: Dual-process accounts of reasoning. *Trends in Cognitive Sciences*, 7(10), 454–459. <https://doi.org/10.1016/j.tics.2003.08.012>
- Evans, J. S. B. (2016). Reasoning, biases and dual processes: The lasting impact of Wason (1960). *Quarterly Journal of Experimental Psychology*, 69(10), 2076–2092. <https://doi.org/10.1080/17470218.2014.914547>
- Fernandes, N. L., Pandeirada, J. N., Soares, S. C., & Nairne, J. S. (2017). Adaptive memory: The mnemonic value of contamination. *Evolution and Human Behavior*, 38, 451–460. <https://doi.org/10.1016/j.evolhumbehav.2017.04.003>
- Fyfe, E. R., & Rittle-Johnson, B. (2017). Mathematics practice without feedback: A desirable difficulty in a classroom setting. *Instructional Science*, 45(2), 177–194. <https://doi.org/10.1007/s11251-016-9401-1>
- Geary, D. C. (2007). Educating the evolved mind: Conceptual foundations for an evolutionary educational psychology. In J. S. Carlson & J. R. Levin (Eds.), *Educating the evolved mind: Conceptual foundations for an evolutionary educational psychology* (pp. 1–99). Information Age.
- Geary, D. C. (2008). An evolutionarily informed education science. *Educational Psychologist*, 43(4), 179–195. <https://doi.org/10.1080/00461520802392133>
- Geary, D. C., & Berch, D. (2015). Evolutionary approaches to understanding children's academic achievement. In R. A. Scott & S. M. Kosslyn (Eds.), *Emerging trends in the social and behavioral sciences* (pp. 1–10). Wiley. <https://doi.org/10.1002/9781118900772.etrds0123>
- Geary, D. C., & Berch, D. (2016). Evolution and children's cognitive and academic development. In D. C. Geary & D. Berch (Eds.), *Evolution and children's cognitive and academic development* (pp. 217–249). Springer International Publishing. [https://doi.org/10.1007/978-3-319-29986-0\\_9](https://doi.org/10.1007/978-3-319-29986-0_9)
- Geary, D. C., & Bjorklund, D. F. (2000). Evolutionary developmental psychology. *Child Development*, 71(1), 57–65. <https://doi.org/10.1111/1467-8624.00118>
- Ginns, P. (2006). Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects. *Learning and Instruction*, 16(6), 511–525. <https://doi.org/10.1016/j.learninstruc.2006.10.001>
- Glenberg, A. M., Goldberg, A. B., & Zhu, X. (2011). Improving early reading comprehension using embodied CAI. *Instructional Science*, 39(1), 27–39. <https://doi.org/10.1007/s11251-009-9096-7>
- Griggs, R. A., & Cox, J. R. (1982). The elusive thematic-materials effect in Wason's selection task. *British Journal of Psychology*, 73(3), 407–420. <https://doi.org/10.1111/j.2044-8295.1982.tb01823.x>
- Handley, S. J., & Trippas, D. (2015). Chapter two-dual processes and the interplay between knowledge and structure: A new parallel processing model. In B. Ross (Ed.), *The psychology of learning and motivation* (pp. 33–58). <https://doi.org/10.1016/bs.plm.2014.09.002>
- Johnson, E. D., Tubau, E., & De Neys, W. (2016). The Doubting System 1: Evidence for automatic substitution sensitivity. *Acta Psychologica*, 164, 56–64. <https://doi.org/10.1016/j.actpsy.2015.12.008>
- Kahneman, D., & Frederick, S. (2005). A model of heuristic judgment. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 267–293). Cambridge University Press.
- Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The expertise reversal effect. *Educational Psychologist*, 38(1), 23–31. [https://doi.org/10.1207/S15326985EP3801\\_4](https://doi.org/10.1207/S15326985EP3801_4)
- Kirschner, F., Paas, F., & Kirschner, P. A. (2011). Task complexity as a driver for collaborative learning efficiency: The collective working-memory effect. *Applied Cognitive Psychology*, 25(4), 615–624. <https://doi.org/10.1002/acp.1730>
- Kirschner, F., Paas, F., Kirschner, P. A., & Janssen, J. (2011). Differential effects of problem-solving demands on individual and collaborative learning outcomes. *Learning and Instruction*, 21(4), 587–599. <https://doi.org/10.1016/j.learninstruc.2011.01.001>
- Leding, J. K. (2018). The animacy advantage in memory: Manipulations of levels of processing and survival processing. *The American Journal of Psychology*, 131(3), 273–281. <https://doi.org/10.5406/amerjpsyc.131.3.0273>
- Lespiau, F., & Tricot, A. (2018). Primary knowledge enhances performance and motivation in reasoning. *Learning and Instruction*, 56, 10–19. <https://doi.org/10.1016/j.learninstruc.2018.02.007>
- Lespiau, F., & Tricot, A. (2019). Using primary knowledge: An efficient way to motivate students and promote the learning of formal reasoning. *Educational Psychology Review*, 31(4), 915–938. <https://doi.org/10.1007/s10648-019-09482-4>
- Lespiau, F., & Tricot, A. (2022a). Primary vs. secondary knowledge contents in reasoning: Motivated and efficient vs. overburdened. *Acta Psychologica*, 227, 103610. <https://doi.org/10.1016/j.actpsy.2022.103610>
- Lespiau, F., & Tricot, A. (2022b). Using primary knowledge in unpopular statistics exercises. *Educational Psychology Review*, 34(4), 2297–2322. <https://doi.org/10.1007/s10648-022-09699-w>
- Mavilidi, M. F., Okely, A. D., Chandler, P., Cliff, D. P., & Paas, F. (2015). Effects of integrated physical exercises and gestures on preschool children's foreign language vocabulary learning. *Educational Psychology Review*, 27(3), 413–426. <https://doi.org/10.1007/s10648-015-9337-z>
- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63(2), 81–97. <https://doi.org/10.1037/h0043158>
- Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, 130(4), 621–640. <https://doi.org/10.1037/0096-3445.130.4.621>

- Nairne, J. S. (2010). Adaptive memory: Evolutionary constraints on remembering. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 53, pp. 1–32). Academic Press. [https://doi.org/10.1016/S0079-7421\(10\)53001-9](https://doi.org/10.1016/S0079-7421(10)53001-9).
- Nairne, J. S. (2016). Adaptive memory: Fitness-relevant “tunings” help drive learning and remembering. In D. C. Geary & D. Berch (Eds.), *Evolutionary perspectives on child development and education* (pp. 251–269). Springer International Publishing.
- Nokes-Malach, T. J., Richey, J. E., & Gadgil, S. (2015). When is it better to learn together? Insights from research on collaborative learning. *Educational Psychology Review*, 27(4), 645–656. <https://doi.org/10.1007/s10648-015-9312-8>
- Paas, F., & Ayres, P. (2014). Cognitive load theory: A broader view on the role of memory in learning and education. *Educational Psychology Review*, 26(2), 191–195. <https://doi.org/10.1007/s10648-014-9263-5>
- Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, 38(1), 1–4. [https://doi.org/10.1207/S15326985EP3801\\_1](https://doi.org/10.1207/S15326985EP3801_1)
- Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review*, 24(1), 27–45. <https://doi.org/10.1007/s10648-011-9179-2>
- Paas, F., & van Merriënboer, J. J. (2020). Cognitive-load theory: Methods to manage working memory load in the learning of complex tasks. *Current Directions in Psychological Science*, 29(4), 394–398. <https://doi.org/10.1177/0963721420922183>
- Ping, R., & Goldin-Meadow, S. (2010). Gesturing saves cognitive resources when talking about nonpresent objects. *Cognitive Science*, 34(4), 602–619. <https://doi.org/10.1111/j.1551-6709.2010.01102.x>
- Richerson, P. J., & Boyd, R. (2005). *Not by genes alone: How culture transformed human evolution*. University of Chicago Press.
- Rohrer, D., Dedrick, R. F., & Stershic, S. (2015). Interleaved practice improves mathematics learning. *Journal of Educational Psychology*, 107(3), 900–908. <https://doi.org/10.1037/edu0000001>
- Roussel, S., Joulia, D., Tricot, A., & Sweller, J. (2017). Learning subject content through a foreign language should not ignore human cognitive architecture: A cognitive load theory approach. *Learning and Instruction*, 52, 69–79. <https://doi.org/10.1016/j.learninstruc.2017.04.007>
- Sparks, A. M., Fessler, D. M., Chan, K. Q., Ashokkumar, A., & Holbrook, C. (2018). Disgust as a mechanism for decision making under risk: Illuminating sex differences and individual risk-taking correlates of disgust propensity. *Emotion*, 18, 942–958. <https://doi.org/10.1037/emo0000389>
- Stanovich, K. E., West, R. F., & Toplak, M. E. (2011). The complexity of developmental predictions from dual process models. *Developmental Review*, 31(2), 103–118. <https://doi.org/10.1016/j.dr.2011.07.003>
- Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science*, 32(1), 9–31. <https://doi.org/10.1023/B:TRUC.0000021808.72598.4d>
- Sweller, J. (2008). Instructional implications of David C. Geary’s evolutionary educational psychology. *Educational Psychologist*, 43(4), 214–216. <https://doi.org/10.1080/00461520802392208>
- Sweller, J. (2016). Cognitive load theory, evolutionary educational psychology, and instructional design. In D. C. Geary & D. Berch (Eds.), *Evolution and children’s cognitive and academic development* (pp. 291–306). Springer International Publishing. [https://doi.org/10.1007/978-3-319-29986-0\\_9](https://doi.org/10.1007/978-3-319-29986-0_9).
- Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. Springer.
- Sweller, J., & Sweller, S. (2006). Natural information processing systems. *Evolutionary Psychology*, 4(1), 434–458. <https://doi.org/10.1177/147470490600400135>
- Toumpaniari, K., Loyens, S., Mavilidi, M. F., & Paas, F. (2015). Preschool children’s foreign language vocabulary learning by embodying words through physical activity and gesturing. *Educational Psychology Review*, 27(3), 445–456. <https://doi.org/10.1007/s10648-015-9316-4>
- Trémolière, B., Gagnon, MÈ, & Blanchette, I. (2017). Cognitive load mediates the effect of emotion on analytical thinking. *Experimental Psychology*, 63, 343–350. <https://doi.org/10.1027/1618-3169/a000333>
- Tricot, A., & Sweller, J. (2014). Domain-specific knowledge and why teaching generic skills does not work. *Educational Psychology Review*, 26(2), 265–283. <https://doi.org/10.1007/s10648-013-9243-1>
- Ünal, Z. E., Forsberg, A., Geary, D. C., & Cowan, N. (2022). The role of domain-general attention and domain-specific processing in working memory in algebraic performance: An experimental approach. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 48, 348–374. <https://doi.org/10.1037/xlm0001117>
- Van Gog, T., Paas, F., Marcus, N., Ayres, P., & Sweller, J. (2009). The mirror neuron system and observational learning: Implications for the effectiveness of dynamic visualizations. *Educational Psychology Review*, 21(1), 21–30. <https://doi.org/10.1007/s10648-008-9094-3>
- Wieckowski, A. T., Flynn, L. T., Richey, J. A., Gracanic, D., & White, S. W. (2020). Measuring change in facial emotion recognition in individuals with autism spectrum disorder: A systematic review. *Autism*, 24(7), 1607–1628. <https://doi.org/10.1177/1362361320925334>
- Youssef, A., Ayres, P., & Sweller, J. (2012). Using general problem-solving strategies to generate ideas in order to solve geography problems. *Applied Cognitive Psychology*, 26(6), 872–877. <https://doi.org/10.1002/acp.2888>