Chapter 5
An Evolving Perspective to Capture Individual Differences Related to Fluid and Crystallized Abilities in Information Searching with a Search Engine

Mylène Sanchiz, Franck Amadieu, and Aline Chevalier

Abstract Interacting with a search engine to search for information is an essential component in our information society. Yet, information search can be a complex task as users can face challenges when processing a staggering amount of information. Research in cognitive psychology and ergonomics has shown important individual differences in search strategies and performance. In this chapter, we describe how fluid and crystallized abilities may influence search behavior all along the task and how they can account for users' difficulties. Our purpose is to provide a theoretical and methodological foundation to better understand the role of these abilities. To this point, we first review recent insights on the behavioral data collected in studies. Next, we present a new framework to analyze such data and discuss how fluid and crystallized abilities can impact information processing when searching for information. Illustrations of how this work can contribute to the development of useful information search support tools are discussed.

5.1 Introduction

In our information and communication society, we process information every day to make informed decisions, to acquire new knowledge, to complete a specific goal, to get up-to-date news or for leisure. The development of the web and information technologies has granted individuals a somewhat easy access to a huge mass of information. Search engines are burgeoning on the web, and despite how intuitive they may look at first, interacting with them to search for information can be complex for some users. The literature on cognitive psychology and ergonomics has documented how children (Bilal and Kirby 2002), disabled adults (Giraud et al. 2018) and older adults (Dommes et al. 2011; Wagner et al. 2010; Sanchiz et al. 2017a, b, 2019a) can face challenges when using a search engine to search for information. Users' difficulties can come from a wide variety of cognitive, social or emotional factors

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(such as low prior topic knowledge, lack of familiarity with the device, low self-perceived efficiency on the web, anxiety toward new technologies) (Hölscher and Strube 2000; Sharit et al. 2008).

The current chapter addresses two particular types of cognitive factors that have received an increased interest over the last few years: fluid and crystallized abilities (Crabb and Hanson 2014; Dommes et al. 2011; Eppinger et al. 2007; Sanchiz et al. 2019a; Sharit et al. 2015). These abilities allow individuals to reason and interact with their environment. Fluid abilities correspond to the ability to think, reason and solve problems independently of learning, experience and education, whereas crystallized abilities refer to the skills and knowledge individuals acquire throughout their life (such as prior knowledge or vocabulary skills) (Cattell 1971; Horn and Cattell 1967). These abilities can impact people's behavior and performance (Park et al. 1996; Park 2000), and they are particularly crucial for problem-solving tasks involving working memory (such as information search). However, their role on information search (IS) with a search engine is still to be better documented, particularly for growing populations of users on the web such as older adults. Better capturing individual differences related to such abilities are crucial in order to: (i) predict adequately the behavior and search performance of users with particular needs and (ii) develop adapted IS support tools. Adopting a cognitive approach to study IS strategies could complement approaches in information science to understand the decisions taken by users with particular needs. For instance, combining cognitive and computing approaches could help future research integrate the impact of users' navigational and processing decisions all along the search task in order to better predict users' difficulties and performance. In addition, such knew knowledge would also provide more validation for the inferences and conclusions drawn from empirical data in the future works.

With this in mind, we will first begin the chapter with a brief overview of the theoretical frameworks of IS that are compatible with the inclusion of fluid and crystallized abilities. Next, a synthesis of the empirical findings related to the influence of these abilities on IS will be provided. Then, we will present an original methodological framework to study the impact of fluid and crystallized abilities on IS performance (i.e., efficiency) and behavior (i.e., searching strategies). The chapter will conclude with the introduction of a new theoretical perspective to guide future research works and better account for the role of fluid and crystallized abilities.

5.2 Current State of the Art on the Role of Fluid and Crystallized Abilities in Information Search Behavior and Performance

5.2.1 Review of the Theoretical Construct of IS

Research in cognitive psychology and ergonomics has defined IS as a complex problem-solving activity that involves several high-level processes such as comprehension, reasoning and decision-making. IS starts with the elaboration of a mental representation of a search need (i.e., user's search goal) and is followed by several cycles in which the user has to evaluate information relevance, select pieces of information that are related to the search goal and possibly navigate between several content webpages (Fu and Pirolli 2007; Sharit et al. 2008, 2015; van Oostendorp et al. 2012). Searching for information with a search engine usually involves three steps: planning, evaluating information and navigating (Sharit et al. 2008, 2015). First, search engines require users to formulate an initial query that represents their search goal and enter it in the search engine box. To formulate their query, users can rely on information provided in the search context (such as the keywords contained in their information need or in the search problem statements) and their prior topic knowledge (Monchaux et al. 2015; Sanchiz et al. 2019a). The production of the initial query corresponds to the planning stage of the activity (Sharit et al. 2008). This initial query will allow the search engine to retrieve a set of links that users can process to access websites. Then, in a second stage, users have to evaluate the relevance of the search results (i.e., analyze the search engine result page—SERP) and select website(s) to open up. In optimal situations, users should process the links provided on the SERP to locate the best way(s) to find their target information (i.e., select the most useful website(s)). Finally, in a third stage, Sharit and his collaborators (2008, 2015) showed that users can process in deeper detail the websites they opened up (i.e., spend time reading information provided on the website or go deeper to it by navigating into several webpages). IS is a cycling activity: Users can move forward or backward through this step as long as their search need is not fulfilled. Users can, for instance, reformulate their query, update their mental model thanks to new pieces of information, evaluate again the SERP to select a new website, consult more SERPs and so on. The cycling aspect of IS represents the critical part of this activity as it may require users to engage in complex and uncertain decision-making. How users strategically decide to process and update information and navigate between pages to solve their search need is often the key to success or failure.

Models of information search describe the mechanisms that underlie the evaluation and the selection of links (SNIF-ACT models by Fu and Pirolli 2007 or CoLiDeS + Pic by van Oostendorp et al. 2012 for instance). Individuals rely on the information link(s) that concentrate(s) the highest information scent (i.e., highest perceived utility with regard to the search goal). Then, through an activation spreading mechanism, pieces of information semantically related to the search goal are activated in memory and help users decide which link to open up. However, using these computing approaches to predict users' search behavior and performance can be difficult because of the cycling and strategic features of IS. While users move forward through their search, they will allocate their attention to a different information. Consequently, the information scent of one particular piece of information will vary all along the task. In other words, some information that was first highly useful and relevant to the search goal might still be relevant but no longer useful for users. In addition, these computing models often fall short of taking into account users' search strategies and inner resources. Yet, they can have a major impact on users' difficulties and search performance. Research in cognitive psychology showed that IS strategies during the different steps of the search can be supported (or impaired) by several cognitive factors related to crystallized or fluid abilities (Dommes et al. 2011; Sharit et al. 2008).

5.2.2 Review of the Theoretical Construct of Fluid and Crystallized Abilities

Fluid abilities involve processing speed, update in working memory, inhibition, attentional focus or cognitive flexibility (Cattell 1971; Chevalier and Chevalier 2009; Horn and Cattell 1967; Eppinger et al. 2007; Slegers et al. 2012). These abilities help individuals plan, coordinate and regulate the cognitive operations required to perform a task. In other words, fluid abilities support adaptive decision-making and allow individuals to switch between different processing strategies in order to adapt to environment changes and constraints (Lindow and Betsch 2019). Fluid abilities support executive functioning (Salthouse et al. 2003) and are particularly critical in IS:

1. *Cognitive flexibility*: ability to switch attentional focus to different stimuli and manipulate at the same time several mental models (Verhaeghen and Cerella 2002). Lower level of cognitive flexibility can increase individuals' sensitivity to interfering or unpredictable input stimuli. This is particularly critical for IS as this activity heavily relies on alternating between the different mental models elaborated (i.e., representation of users' search goal, of the different search results, websites processed, etc.).
2. *Inhibition*: ability to access, suppress and restrict access to information in working memory (Hasher and Zacks 1988). Inhibitory mechanisms help individuals allocate attentional resources to more goal-relevant items and filter useless information (for instance in reading comprehension). Inhibition can thus be a key to support the exclusion of seductive, salient or irrelevant pieces of information in an environment in which a huge mass of information is easily accessible. Interestingly, goal-directed inhibitory mechanisms are particularly crucial during the

initial stage of IS to avoid the allocation of resources to irrelevant items. Additionally, empirical studies also demonstrated that inhibitory mechanisms could work as a "search and destroy" process (Kawashima and Matsumoto 2018; Moher et al. 2014): While proceeding through a task, the irrelevant items to be ignored are first selected and then inhibited in favor of more relevant items.

3. *Update in working memory*: ability to maintain in working memory an active and up-to-date mental representation. This mechanism helps, for instance, individuals replace pieces of information that are no longer accurate or needed by more relevant ones (Morris and Jones 1990). Three components are at stake in updating mechanism: retrieval, transformation and substitution of information (Ecker et al. 2010). As such, this process allows users to maintain the mental representation of their search need active in working memory and transform it in order to adapt to situational changes (such as the discovery of new information that invalidates previously read ones).

Crystallized abilities correspond to skills and knowledge that an individual acquires throughout life (Cattell 1971; Sharit et al. 2008). They include prior knowledge, knowledge schemata or vocabulary skills. Crystallized abilities are particularly useful to perform actions in an optimal way (i.e., without engaging too much cognitive resources). For instance, when navigating in an environment (as in an unknown train station for instance), individuals may engage automatic processes if they do possess relevant schemata (e.g., find the main hall and train departure/arrival information to know where to go next). Such schemata, acquired through experience, eventually support the planning and executions of actions without much effort.

5.2.3 Overview of the Relation Between Fluid and Crystallized Abilities and IS Behavior and Performance

A large body of research has shown how fluid and crystallized abilities can impact strategies in visual search tasks. For instance, when individuals are asked to locate a target item (e.g., a word and a figure), inhibition mechanisms support the filtering of irrelevant distractors and the localization of relevant items (Kawashima and Matsumoto 2018). However, fewer researches have documented the impact of fluid abilities on information search with search engines or websites. Prior findings have reported that fluid abilities affect search performance and the elaboration of appropriate search strategies (Chin et al. 2009; Pak and Price 2008; Sharit et al. 2008, 2015). For instance, when users have to search for information in a complex fact-finding search task, low cognitive flexibility can alter the number of query reformulations and the number of new keywords produced by participants (Dommes et al. 2011; Crabb and Hanson 2014). Cognitive flexibility is also reported to support the processing of websites' structures and the decision to explore a larger part of the problem space of the search (Brand-Gruwel et al. 2009; Chin et al. 2015).

Crystallized abilities, such as prior topic knowledge or vocabulary, can support users' search performance (Downing et al. 2005; Hölscher and Strube 2000; Monchaux et al. 2015; Sanchiz et al. 2017a; Tabatabai and Shore 2005) and the production of more relevant keywords (Vakkari et al. 2003; Wildemuth 2004). Prior knowledge and IS skills are among the most common dimensions of crystallized abilities used in empirical studies (Downing et al. 2005; Duggan and Payne 2008; Hembrooke et al. 2005; Hölscher and Strube 2000; Monchaux et al. 2015; Sharit et al. 2008, 2015; Tabatabai and Shore 2005; Wildemuth 2004). Prior topic knowledge corresponds to declarative (i.e., semantic content), procedural (knowledge about specific strategies on how to process concepts for instance) and/or metacognitive knowledge (knowledge about how to self-evaluate and regulate the strategies engaged for instance) that are related to a particular knowledge domain (i.e., topic). IS skills correspond to more domain-independent expertise in IS itself (such as the development of relevant schemata to apply or search strategies) (Smith 2015). Prior knowledge, IS skills and more largely crystallized abilities influence how users allocate their resources when processing information (Hölscher and Strube 2000; Monchaux et al. 2015). Prior empirical works have indeed demonstrated that prior topic knowledge supports the formulation of semantically more appropriate keywords (Vakkari et al. 2003; Wildemuth 2004), of more relevant reformulation strategies (such as using more unique queries or making more important transformations when reformulating queries: Hembrooke et al. 2005; Zhang et al. 2005) and search performance (Downing et al. 2005). Prior knowledge can also help users select more relevant websites (Hölscher and Strube 2000) and evaluate information more rapidly (i.e., greater number of webpages visited in a smaller amount of time (Sihvonen and Vakkari 2004; Wildemuth 2004).

Overall, these findings show that prior knowledge and more largely crystallized abilities foster the elaboration of a more coherent mental model of the search need, the articulation of more accurate queries and more efficient processing of information. Hence, low topic knowledgeable users face a double challenge. First, they tend to start searching for information with a less coherent mental model and a less accurate query (which will degrade the quality and relevance of the results retrieved by the search engine). Secondly, less knowledgeable users have fewer resources to evaluate information relevance and to integrate information while they proceed through the search. In sum, crystallized abilities, such as prior knowledge use, can help users process information more efficiently, at lower cognitive costs. They can also improve the relevance and accuracy of the search strategies elaborated.

As illustrated in the above section, a large number of empirical works have documented the impact of crystallized abilities on IS performance and behavior. However, fewer studies examined how fluid abilities can influence users' behavior. In addition, the majority of these empirical studies focused either on large scope indicators of search behavior (such as the time spent searching for information: Sharit et al. 2008, 2015, or the number of queries produced: Dommes et al. 2011) or on very precise indicators but they failed to relate them to the cognitive processes they reflect (such as the number of new keywords produced in query or the query length, e.g., Hembrooke et al. 2005). To fully understand how fluid and crystallized abilities can impact search behavior, research needs to provide a more global framework to analyze these data. Such ambition is quite a challenge as many indicators can be confusingly used as a proxy of several cognitive or metacognitive processes. For instance, the number of queries produced by users can reflect deeper processing (i.e., cognitive processes, such as comprehension or inference-making) or regulation strategies (i.e., metacognitive processes). In the present chapter, we argue that one way to override this challenge would be to identify high-level common features between online indicators (i.e., *do they reflect an attempt to access new information? to keep digging for particular pieces of information?*) and/or contextualize their analyses with regard to the different steps of the activity.

5.3 The Value of Studying Behavioral Data: A Review of Methodological Perspectives to Better Understand the Role of Fluid and Crystallized Abilities

A burgeoning amount of empirical studies use online data to investigate users' search performance and strategies. For instance, indicators of efficiency include the time spent to perform the task (Chin and Fu 2010; Kammerer and Gerjets 2014; Karanam and van Oostendorp 2016; Lazonder et al. 2000; Sharit et al. 2015; Thatcher 2006; Vanderschantz and Hinze 2017) or the task completion speed (i.e., time taken to complete the search task in relation to the success or failure, Aula and Nordhausen 2006; Sanchiz et al. 2017a, b). A staggering amount of indicators of online search strategies can be found in the literature:

- Querying: number of queries formulated, number of new keywords, semantic depth of queries, types of query reformulations, etc (Bilal and Gwizdka 2018; Dommes et al. 2011; Hembrooke et al. 2005; Hölscher and Strube 2000; Monchaux et al. 2015; Phan et al. 2007; Sanchiz et al. 2017a, b, 2019a; Thatcher 2006; Vakkari 2001; Vanderschantz and Hinze 2017; van Deursen and van Dijk 2009).
- Navigational behavior: number of websites visited, number of content webpages opened up, time spent processing websites, etc (Barsky and Bar-Ilan 2012; Downing et al. 2005; Duggan and Payne 2008; Hölscher and Strube 2000; Sanchiz et al. 2017a, b; Scholer et al. 2013).

As a reminder, one of the main challenges in accurately using online data to understand users' search strategies is that most empirical findings analyze behavior to get a better understanding of what users *do* and *why*. However, most of these studies fall short of relating such data to the processes they may reflect. Among the many examples we could cite, Bilal and Kirby (2002) showed in a study that children were less capable than adults to effectively recover from breakdowns or impasses by adapting their search strategies (such as using new keywords in their queries). Such findings could reflect the impact of lower fluid abilities (which are not fully developed at this age), but it was not empirically investigated in the study. In addition, online behavioral indicators can sometimes be difficult to analyze as they may ambiguously represent several cognitive or metacognitive processes from one study to another. For instance, in the literature, the time spent processing the search results on a search engine result page is allotted to either deeper processing (i.e., a cognitive process), planning or evaluating (i.e., metacognitive processes) (Chin and Fu 2010; Dommes et al. 2011; Hahnel et al. 2018; Sharit et al. 2008). Hence, better relating online indicators to the actual processes they underlie and improving the methodological and theoretical frameworks used to analyze them would most likely help future research: (i) use online data with more precision and (ii) make more reliable conclusions about users' search strategies.

In the following section, we will discuss a new theoretical and methodological framework for the analysis of online behavioral data that accounts for the role of fluid and crystallized individual differences. First, we will present how using online indicators to distinguish between exploration and exploitation processes can better illustrate the role of fluid and crystallized abilities in IS. Secondly, we will highlight how contextualizing the analysis of online data to the search context and the different stages of IS can provide crucial insights on users' behavior, performance and cognitive processes.

5.3.1 Distinguishing Exploration Vs. Exploitation

Current empirical research provides interesting insights on users' search behavior and performance. For instance, we are better aware of the search strategies that can account for children's lower search performance (Bilal and Kirby 2002). Research has documented how users process information on websites (i.e., the time they spent reading content on websites for instance), how they explore the problem space (by consulting a new website for instance, Sharit et al. 2008, 2015) and how they can overcome impasses (by reformulating for instance, Bilal and Kirby 2002; Dommes et al. 2011). With regard to the theoretical models of IS (Brand-Gruwel et al. 2009; Fu and Pirolli 2007; Sharit et al. 2008, 2015; van Oostendorp et al. 2012), what readers are asked to do when searching for information (no matter if it is an explicit fact-finding task or a more complex sense-making search task, Bell and Ruthven 2004) is to *process information* and *explore their environment*. *Processing information* in IS implies assessing information relevance, selecting relevant information, comprehending semantic content, elaborating a coherent mental representation of the information retrieved (Hahnel et al. 2018; Sharit et al. 2008, 2015). *Exploring the environment* in IS implies selecting sources of information, navigating between different content webpages or websites, understanding how online documents are structured, how we can interact with them, etc (Sharit et al. 2008, 2015). In other words, indicators reflecting strategies to extensively navigate in different sources of information and initiate new branches/navigational paths in order to process an additional part of the problem space tend to reflect exploratory behavior.

Exploration processes are well documented in the literature. However, studies do not always refer to indicators of exploration as such. Instead, studies mostly refer to navigation or browsing behavior. Chin and her collaborators (2015) detailed the distinction between exploration and exploitation search strategies in IS. In line with information foraging theories (Pirolli and Card 1999), to search for information, individuals can either spend resources to forage for information among a particular source (or group of sources) of information or switch to a new one if the initial source(s) selected turned out to be useless/ not relevant. Due to the limited capacity of their working memory, individuals do not possess extensive resources to search for information. Hence, information searchers need to set a trade-off in order to decide whether or not to engage additional resources. Information foraging theories suggest that the likelihood for users to leave their current sources of information to consult a new one will increase if the expected additional value of visiting a new website exceeds the costs it will demand (Chin et al. 2015; Pirolli and Card 1999; Fu and Pirolli 2007). Indeed, deciding to leave a source of information and switch to a new one can be demanding as it requires users to engage resources to evaluate new information, select a new website, understand how this new website is structured, etc. Switching to a new source of information (i.e., exploring a broader part of the problem space of the search) requires high fluid abilities such as cognitive flexibility. In other words, exploration behavior corresponds to the initiation of new branches (as reflected by opening up a new website, for instance, or reformulating a new query) (Chin et al. 2015; Sanchiz et al. 2019b).

In contrast, exploitation behavior corresponds to perseveration behaviors (i.e., extended processing of similar pieces of information) such as visiting a high number of webpages from the same website (e.g., number of webpages revisited, Duggan and Payne 2008). Indicators reflecting deeper processing of the navigational branches elaborated tend to reflect exploitation strategies (Chin et al. 2015; Sanchiz et al. 2019b). For instance, to reformulate their queries, users can decide to change the entire content of their query, change some of the keywords (e.g., add/retrieve some keywords and change keywords by synonyms) or transform the organization of the query content (e.g., reverse keyword order). In empirical studies, some querying indicators correspond to narrow changes such as step-by-step reformulation strategies or reformulations that heavily rely on the content of the former query produced (i.e., number of times a keyword is reused and broadness of change in query reformulation; see Table 5.1 for example). Such indicators tend to reflect exploitation strategies: Users remain on similar or semantically extremely close information patches to search for information. In contrast, reformulation strategies that reflect broader changes (such as complete query transformation or production of new keywords) show exploration strategies (i.e., the new query formulated will most likely lead to a new and semantically more distant information patch). Table 5.1 provides a synthesis of indicators currently used in empirical works that tend to reflect exploitation strategies. To sum up, exploitation strategies mainly refer to: (i) the time spent processing the search paths initiated and/or (ii) the depth of the processing of the search paths initiated (i.e., the number of websites opened up per query, the number of SERPs consulted per query, etc.).

Table 5.1 Examples of online indicators reflecting exploitation strategies used in current research

Dimension	Indicators	Authors	Type of exploitation behavior
Website selection	Number of websites opened from SERPs per query	Duggan and Payne (2008), Guan (2014), Huang and Efthimiadis (2009)	Exploitation of a search path initiated by formulating a query
	Time taken on SERPs to select a link to visit	Chin and Fu (2010), Kelly et al. (2015)	
	Number of repeated links selected from SERP visits before adjusting queries (i.e., reformulating)	Vanderschantz and Hinze (2017)	
Webpages processing	Number of switches between content pages once on a website	Barsky and Bar-Ilan (2012), Lei et al. (2013), Wildemuth et al. (2018), Dommes et al. (2011)	Exploitation of a search path initiated through the visit to a website
	Number of content pages opened up per website visited	Chin et al. (2015) and Sanchiz et al. (2019b)	
	Number of content webpages visited multiple times	Barsky and Bar-Ilan (2012), Lei et al. (2013), Wildemuth et al. (2018)	
Query formulation	Number of times keywords/terms are used in queries	Hembrooke et al. (2005)	Exploitation of a search path initiated through a query formulation
	Number of keywords extracted from instructions/search problem statements	Dommes et al. (2011) and Sanchiz et al. (2017a, 2019a)	
	Broadness of changes in query reformulation	Hembrooke et al. (2005), Hölscher and Strube (2000), Vakkari (2001)	

It is to be noted that exploration and exploitation strategies cannot be generally associated with either good or bad search strategies per se (and thus cause good or bad performance). To determine whether exploring or exploiting information turns out to be the relevant thing to do, one must consider the search context (i.e., search goal and current stage of the activity) and the relevance of the information being processed. The following part of this section will discuss how research can connect online data with either exploration or exploitation strategies for navigation and querying. Figure 5.1 presents a schematic overview of the theoretical and methodological framework presented in this chapter.

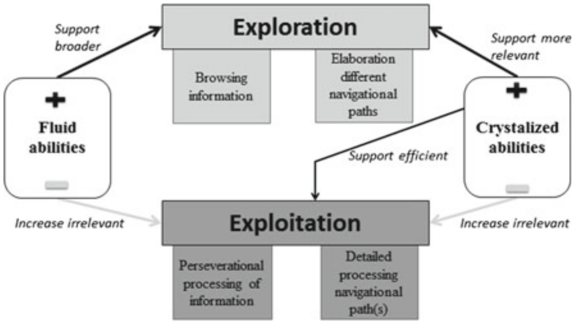

Fig. 5.1 Overview of the role of fluid and crystallized abilities in exploration and exploitation search strategies

5.3.2 Presentation of the Construct of Exploration and Exploitation Behavior

As discussed in the above section, current research is burgeoning with online indicators showing how users navigate the web to search for information. Indicators of website selection, content webpage visits and time allotted to processing SERPs on webpages are among the most commonly used ones (Aula and Nordhausen 2006; Barsky and Bar-Ilan 2012; Dommes et al. 2011; Gerjets et al. 2011; Hölscher and Strube 2000). These indicators are particularly useful to understand to what extent users are engaged in an exhaustive or a superficial way in the task. However, it may be tricky to fully understand users' behavior without confronting these variables one with another (and thus get a clearer global representation of users' navigational behavior) and with the cognitive processes they reflect. As illustrated in Fig. 5.1, from a methodological point of view, the exploration–exploitation discrepancy can help research categorize raw data into two types of navigational behavior: (i) strategies to browse and process a broad part of the problem space and (ii) strategies to maximize the hoped utility of the sources of information accessed by digging deeper into them.

Discriminating different patches of information (i.e., the different sub-parts of the problem space) can be difficult (Chin et al. 2015). Indeed, users may go for another source of information, such as a new website, but they may keep looking for the same pieces of information. For instance, when searching for the name of *Luke Skywalker's ship* in the *Star Wars movies*, users may start by opening the first result provided on the SERP list and then go back to the SERP to open up a new one and look for further information. Consistently with prior works (Chin et al. 2015; Sanchiz et al. 2019b), we argue that initiating a new search path corresponds to exploration. New search paths can be elaborated through the evaluation of SERPs and the selection of new websites not previously seen or through a new query reformulation. Of course, exploratory behavior can be more or less extensive. Users may switch between two patches of information (i.e., parts of the problem space) that are semantically very similar. In contrast, users may also perform wider jumps between information patches. For instance, opening up a *Wikipedia* page tackling the different *ships* in *Star Wars* and jumping to a new website detailing the differences between the *Jedi* and the *Empire spaceships* correspond to a close jump (i.e., these two websites will most likely share a lot of common information). In contrast, returning to the SERP to open up a website describing the scenario of *Star Wars IV: A New Hope* corresponds to a wider jump as it focuses on more different pieces of information. Similar remarks can be made for querying strategies. Initiating a new search path is done by reformulating. To reformulate a query, either users can change parts of their previous query (i.e., transform, add or erase some keywords) or they may transform it completely (and use new keywords) (Bilal and Gwizdka 2018; Dommes et al. 2011; Duggan and Payne 2008; Kroustallaki et al. 2015; Lei et al. 2013; Sanchiz et al. 2017a, b, 2019a; Wildemuth et al. 2018). Complete reformulations, new keywords, unique queries are querying indicators reflecting a wide jump to a new information patch, whereas changing query length, suppressing keywords, keeping keywords used in the previous query correspond to a narrow jump.

5.3.3 *Impact of Fluid Abilities on Exploration and Exploitation Behavior*

Theoretically, fluid abilities mainly influence how individuals perform a task (i.e., the strategies engage to solve a problem for instance). In IS, fluid abilities support changes of search strategies in order to adapt to the constraints of the environment (Sharit et al. 2008, 2015). As discussed previously, exploratory behavior corresponds to more flexible search strategies in which users turn to different sources of information or different search patches to solve their search need (Sanchiz et al. 2019b). For instance, prior works have shown that fluid abilities such as cognitive flexibility can predict the number of reformulations and visits to new websites (Dommes et al. 2011; Sharit et al. 2008). Allocating extra resources to opening up a new website or reformulating queries requires users to: develop a new mental representation of the additional search path initiated, keep it active in working memory, update the overall global mental model of their search and inhibit some information already activated to put them on a second plan. All these processes particularly rely on users' fluid abilities. Indeed, current research has shown that users with lower fluid abilities (such as older adults) tend to visit fewer websites, reformulate less and initiate a smaller number of different navigational paths (Dommes et al. 2011; Sanchiz et al. 2019a, b). As another example, one could also cite how children with low fluid abilities tend to have difficulties to overcome impasses and reformulate less often (Bilal and Kirby 2002).

In a nutshell, fluid abilities, by supporting adaptation to environment changes and processing strategy switch (Eppinger et al. 2007; Sharit et al. 2008), tend to play a major role in broad exploration strategies and the development of adapted decisions when facing a breakdown. Indicators reflecting the will to find new information (i.e., exploratory behavior) can thus help research better grasp the actual role of fluid abilities in IS behavior. Operationally, when searching for information, users are more likely switching between exploration and exploitation strategies (i.e., users tend to initiate new branches/search paths and then process them in greater detail). Hence, high or low levels of fluid abilities will influence the trade-off between exploration and exploitation behaviors (Chin et al. 2015; Sanchiz et al. 2019b). Individuals with higher levels of fluid abilities should develop a larger proportion of exploration strategies. In contrast, for users with lower fluid abilities, the trade-off between exploration and exploitation strategies should be in favor of exploitation behavior (i.e., indicators of deeper processing of websites, multiple subsequent uses of similar keywords, etc.).

5.3.4 Impact of Crystallized Abilities on Exploration and Exploitation Behavior

Crystallized abilities, such as prior knowledge use or vocabulary skills, contribute to information processing efficiency (i.e., accurate evaluation of information relevance, efficient selection and integration of information, etc.) (Hölscher and Strube 2000; Monchaux et al. 2015; Sharit et al. 2008, 2015). In line with prior empirical studies reported in this chapter, we argue that crystallized abilities foster exploration strategies that are more relevant (e.g., selection of websites relevant with regard to users' search goal, production of accurate queries, etc.). For instance, high knowledgeable users should have enough cognitive resources available to browse a greater amount of information and elaborate a greater number of different navigational paths. Studies investigating the impact of IS skills showed that highly skilled searchers tend to conduct more parallel searches (such as processing several websites in multiple tabs) (Thatcher 2006). In contrast, less knowledgeable users tend to exhaust their cognitive resources in sense-making and coherence maintaining while processing information, which does not allow them to explore efficiently a broader part of the search problem space. In addition, crystallized abilities should support the efficient exploitation of the information patches consulted by users (see Fig. 5.1 for an overview). For instance, prior knowledge, vocabulary skills and IS skills can reduce the time spent processing information. They can also support the selection of coherent webpages once on a website through a more accurate evaluation of the website menus (Dommes et al. 2011; Hölscher and Strube 2000; Pak and Price 2008; Sanchiz et al. 2017a). In contrast, lower levels of crystallized abilities should reduce exploration strategies and increase the exploitation of irrelevant search patches. For instance, users with lower levels of prior topic knowledge or IS skills tend to narrow down their search activity and focus on a small amount of websites (link-dependent search strategies, Thatcher 2006) or visit a greater number of webpages once on a website (Sanchiz et al. 2017a).

Analyzing the impact of crystallized abilities on exploitation strategies represents a great challenge. Indeed, several empirical findings have clearly demonstrated to what extent these abilities can support more efficient and accurate exploration (or decrease exploration for users with lower crystallized abilities). However, very few studies have investigated how low levels of crystallized abilities can cause more unadapted exploitation of information patches (i.e., cause users to persevere on processing irrelevant sources of information). Indeed, to do so, research should first determine what is an irrelevant search path (an irrelevant website or query for instance). In IS, relevance is determined with regard to the features of the user's search goal (or the environments' constraints) (Balatsoukas and Ruthven 2012). When investigating navigation behavior, relevant sources of information thus correspond to sources that contain the target information or to webpages/websites that users have to go through in order to solve the search problem (either because these pages contain useful information to develop a more coherent mental representation of the search need or because the organization of the documents itself does not allow to jump over these pages). For some tasks, as in explicit fact-finding ones (Bell and Ruthven 2004), evaluating which sources of information are relevant can be easy. For instance, the level of topicality (i.e., semantic proximity between the website's contents and the search goal) and the quality of the source of information (i.e., credibility, authoritativeness of the author, etc.) are somewhat easy parameters to take into account in order to determine information source relevance. However, for more open-ended, sense-making and imprecise search tasks, such criterion might be more difficult to use. Indeed, when searching for information with a vague and unclear representation of the search need, users may deliberately want to access easy-to-understand documents that may not be the most relevant ones but that contain intuitive and familiar pieces of information that could contribute to get a clearer idea of what needs to be done to locate the target information. In other words, opening up a website that provides a general broad overview of a topic and browsing more or less randomly several webpages on this website could be considered as irrelevant exploitation behavior; yet, when considering the search context and the stage of the activity (i.e., early beginning of the search) such behavior may not necessarily be irrelevant.

Indeed, exploitation strategies mainly correspond to the over-processing of the search paths initiated through query formulation or website selection (Chin et al. 2015; Sanchiz et al. 2019b). However, to draw coherent conclusion on users' search behavior, researchers need to discriminate between coherent and necessary exploitation of information (i.e., such as deeper processing of useful webpages) and abusive/perseverating processing of information (such as going in circles and revisiting multiple times the same webpages). Ideally, to do so, researchers should distinguish between relevant/useful content and irrelevant ones. Some computerized tools may provide support to evaluate the semantic relevance of the links consulted for instance (see latent semantic analysis—LSA—as used in the CoLiDeS + Pic model by van Oostendorp et al. 2012). However, using LSA requires first to construct a database of documents in order to compute the degree of relevance of each link visited by users. Another less costly way to determine useful exploitation strategies *vs* irrelevant perseverating/exploitation strategies would be to distinguish between initial in-depth processing and subsequent ones. For instance, as stated earlier, the number of webpages consulted per website or per query is a commonly used indicator that reflects exploitation strategies (Barsky and Bar-Ilan 2012; Duggan and Payne 2008; Guan 2014; Huang and Efthimiadis 2009; Lei et al. 2013; Wildemuth et al. 2018). In line with Duggan and Payne's work (2008), research could take into account the number of different pages visited per query (or unique pages opened up per query) and the number of multiple visits to previously consulted webpages per query. Such indicator does not provide any information on the actual relevance or usefulness of the webpages consulted. However, it does distinguish between exploitation behavior that can reflect strategies to extensively comprehend the topic or process a search path and exploitation behavior that reflect more disorientation, unadapted decision-making or browsing difficulties. In addition, refining indicators of exploitation in such way could also improve the predictive power of search behavior on performance as exploitation behavior related to browsing difficulties (i.e., difficulties to select a useful webpage to visit) or disorientation is often associated with lower search performance (Wagner et al. 2010).

5.4 Contextualizing

5.4.1 Contextualizing Online Behavioral Data in Relation to the Evolution of the Search Behavior

As outlined in the previous section, indicators of exploration and exploitation strategies may provide more accurate insights on users' search behavior. However, to predict search performance (and thus relate exploration and exploitation strategies to IS outcome), one most likely needs to take into account the context of the search. One intuitive finding to understand how crucial it is to take into account the search context is the analysis of chronometry. Several prior works investigated, for example, the time spent processing the SERPs before selecting a link/website to open up (Chin and Fu 2010; Dommes et al. 2011; Kammerer and Gerjets 2014; Sanchiz et al. 2017a, 2019a). These studies showed, for instance, that users facing difficulties to select a relevant source of information can spend longer dwell times evaluating the search engine results. However, the value of the time spent processing the SERPs can be tremendously different from one task to another. For instance, in a simple fact-finding search task, such as "*when was Star Wars IV released in theaters?*", no particular search strategies are required (provided that the user does formulate a relevant query that includes all important keywords). To find the target information, users need to read the top of the SERP in order to find the answer or to visit one website provided at the top of the result list to find it. In such cases, extensive dwell time spent on the SERP may reflect difficulties. However, in a more complex open-ended task, such as "*Which French political TV show, presented by two famous journalists has received political celebrities such as Georges Marchais and Francois Mitterrand in the seventies?*", users most likely need to allocate more effort to the processing of the SERP in order to select one (or several) website(s) to find the target answer. In such contexts, dwell time on SERPs may not necessarily reflect difficulties but rather engagement in the task or careful processing. As illustrated in this example, the context of the search is determined by several factors such as the source of the information need (intern or extern) and the type of search task to perform (i.e., the complexity of the task and the constraints it puts on users). Taking into account the context of the search is particularly crucial to understand users' behavior and predict/explain search performance. Indeed, tasks of varying complexity do not require the same processes or the same amount of cognitive resources and they do not all share the same constraints for users. Bell and Ruthven (2004) presented a typology of search tasks in which the level of certainty/clarity of the information to be found and the way to access it represent major criteria of complexity. For instance, when the information to be found and the way to access it are clearly defined (the instructions provide relevant clues such as useful keywords: Dommes et al. 2011; Sanchiz et al. 2017a, b, 2019a) users are not particularly required to extensively process websites. In such context, deeper processing, such as a great number of different websites or multiple query reformulations, most likely reflects exploitation behavior. In contrast, when the search process is highly imprecise and uncertain, users are expected to process a greater amount of information and navigate in many websites to gather pieces of information (Chin and Fu 2010; Sanchiz et al. 2017a, b). In more complex search contexts, the above-mentioned indicators most likely reflect exploration strategies, at least at the early stages of the search.

Hence, one key to better analyze users' exploration and exploitation strategies and thus understand the respective role of fluid and crystallized abilities is to extract what users have to do to solve the search task (i.e., extract through a cognitive analysis the processes that users need to engage in order to be successful). No matter the level of complexity, or the amount of resources that users have (thanks to his/her own prior knowledge or thanks to a support tool), search tasks of similar nature (i.e., fact-finding ones, open-ended ones, sense-making ones, etc.) share some common general features that can help researchers make sense of the behavioral data they collect. As presented in Bell and Ruthven (2004) classification of task complexity, the more complex the task is, the more it requires exploration and exploitation strategies. However, as discussed above, understanding the task demands may sometimes not be enough to discriminate between exploration and exploitation strategies. In such cases, contextualizing the data collected (i.e., analyzing the data with regard to the ongoing step of the search) may bring more relevant insights.

5.4.2 Contextualizing Online Behavioral Data in Relation to the Search Task

Current indicators used in the literature provide a good overview of the strategies used during the entire search activity. These indicators tackle a wide spectrum of processes related to the exploration and exploitation of information in IS with a search engine. However, as outlined earlier in this chapter, research most often falls short of analyzing how users' search strategies evolve while proceeding through the task. Theoretical models of IS have explained how the different stages of the activity can rely on different processes. For instance, Sharit and collaborators (2008, 2015) showed that stage one particularly requires planning and the elaboration of a coherent mental representation of the search need/initial query. The second stage of the activity relies on evaluation processes (i.e., to assess information relevance and select websites). In contrast, the last stage of the activity requires navigation, sense-making processes to integrate information. This stage also requires users to maintain relevant information active in working memory and update them throughout the task. Finally, due to the cycling nature of IS, users may switch between these different stages, which particularly requires flexibility, evaluation and regulation processes. Hence, to draw stronger conclusions on users' search behavior and better predict search performance, analyzing online data with regard to the different stages of the activity represents a promising perspective.

Considering the different stages of IS is a burgeoning trend in the literature. For instance, prior works have developed operational indicators to understand how users start searching for information (such as the quality of the initial query produced and the time taken on the first SERP to access a website) (Downing et al. 2005; Kammerer and Gerjets 2014; Lei et al. 2013). Other studies developed indicators to investigate how users switch between browsing the web to process information and rereading the search problem instructions (to reactivate information in working memory for instance, Vakkari et al. 2003). In addition, studies focusing on information evaluation in Google-like environments (such as the SERP list) also created specific indicators based on eye-tracking measures to analyze how users initially process a search engine result before selecting a website (for instance: duration of the first-path fixation on a link or the duration of the first saccade, Oulasvirta et al. 2005: for a review, see Alemdag and Cagiltay 2018).

Analyzing the initial stage of the search is especially interesting because it can reflect how users engage in the task based on their own abilities and the information provided in the context without being influenced by how they processed information during the search (Sanchiz et al. 2017b). Hence, as illustrated in Table 5.2, retrieving precise indicators during the planning stage can help researchers identify whether users develop more exploratory strategies or exploitation strategies in relation to their fluid and crystallized abilities. For instance, Chin and Fu (2010) and Sanchiz and her collaborators (2017b, 2019b) showed that young adults (around 20 years old) used more bottom-up strategies when selecting the first website to open up (i.e., extremely short time spent on SERP before opening up a website and selection influenced by link position on the SERP list). In contrast, older adults (aged 60 years old and more) with lower fluid abilities used more top-down strategies and took more time to evaluate the SERP (i.e., they spent longer time on the initial SERP retrieved before deciding to opening up a website and mostly relied on their topic knowledge rather than link position).

In addition, computing indicators reflecting planning, evaluation, navigation and regulation stages of the activity can provide further insights to understand users'

Table 5.2 Examples of indicators investigated during the initial stage of the search in the literature (i.e., planning, Sharit et al. 2008, 2015)

Process targeted	Indicator	Author	Dimension of IS
Querying	Semantic specificity of initial query produced	Lei et al. (2013)	Level of relevance of the early mental representation elaborated (as measured by the semantic relevance of the query)
	Number of keywords extracted from the search problem statements in the first query	Sanchiz et al. (2017b)	Level of relevance of the early mental representation elaborated + inhibition of instruction-based keywords
	Number of new keywords (inferred by users based on their own prior knowledge) in the first query	Sanchiz et al. (2017b)	Level of relevance of the early mental representation elaborated + cognitive flexibility (adding new keywords)
	Analysis of the keywords contained in the initial query and query length	Jansen et al. (2007), Guan (2014), Vakkari (2001)	Level of relevance of the early mental representation elaborated + inhibition and cognitive flexibility
Navigation/website selection	Time taken to access the first relevant article	Downing et al. (2005), Kammerer and Gerjets (2014)	Evaluation of information relevance and sources
	Time spent evaluating the initial SERP	Sanchiz et al. (2017b, 2019b)	Evaluation of information
	Impact of the first query produced (number of websites accessed from initial SERP)	Guan (2014)	Level of exploitation of initial query
	Level of relevance of the initial document selected	Scholer et al. (2013)	Quality of evaluation processes

exploration and exploitation behavior. First, during the initial stage of the search, users try to reinforce the coherence of their mental representation of the search need (i.e., by extracting new information from the initial SERP or website and by determining whether the initial query produced is really relevant or not). At this stage, good information searchers should thus activate relevant prior knowledge and show flexible strategies in case they started the search with an irrelevant query or opened up an irrelevant website. In more complex open-ended tasks (Bell and Ruthven 2004), when the search need is imprecise, good searchers should more heavily rely on exploration strategies in order to browse a greater amount of information and find relevant pieces of information to improve their mental representation of the search need (and reformulate a better query). In contrast, exploitation of the initial search path elaborated (through the first query and/or the first website opened) might reflect a less adapted strategy. Stages 2 (evaluation) and 3 (deep processing) may however include a larger proportion of exploitation strategies as these two stages require users to process the relevance of the search path they elaborated (and thus determine whether it is a good way to find the target information or if they should switch back to earlier stages and regulate their behavior). Hence, exploitation of the search paths elaborated may, at first, not show particular difficulties. However, as users proceed through the search (for instance, after several phases of regulation such as multiple query reformulations), accumulation of exploitation strategies (such as extensive processing of a website through a larger number of content webpages accessed) most likely reflects that users face difficulties or are disoriented.

Finally, the number of SERPs—website switches and the number of query reformulations during the transitions between stages—could reflect adapted regulation strategies supported by the efficient use of fluid abilities (and thus reflect higher level of exploration).

5.5 Discussion

5.5.1 Theoretical Perspectives to Include Fluid and Crystallized Abilities to Theoretical Models

Overall, the current chapter discussed how aggregating online indicators as exploration or exploitation search strategies can help future research better understand the effects of interindividual differences related to fluid and crystallized abilities on IS behavior and performance. On a theoretical plan, the framework presented pointed out that IS requires two types of processes: (i) keeping active and refreshing information in working memory and (ii) processing information. Figure 5.2 provides a synthetic overview of the theoretical framework of IS that we introduce in order to better analyze how crystallized and fluid abilities impact IS performance and behavior.

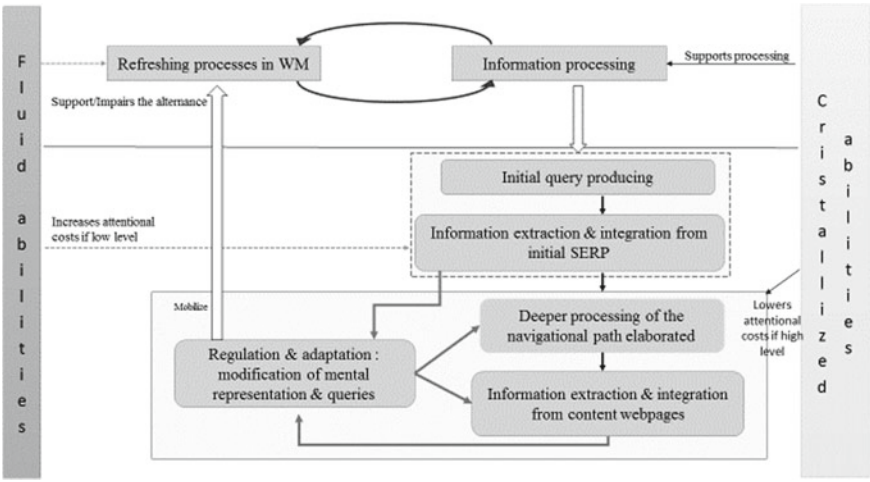

Fig. 5.2 Overview of the new theoretical framework to account for the role of fluid and crystallized abilities on IS

In line with several cognitive models of IS (Sharit et al. 2008, 2015), the information processing component of IS involves a wide set of processes such as elaborating mental models, evaluating information relevance and sources, etc. As illustrated in Fig. 5.2, information processing is argued to happen while users have to allocate resources to maintain information active and up to date in their working memory. For instance, users allocate their resources to elaborate a coherent mental representation of their search need and of each new source of information processed (and update their mental representation) in parallel to engaging in processing information (such as validating information, comprehension processes, sense-making). To perform these two types of processes in parallel all along the activity can particularly pose high demands on cognitive resources. Users' fluid and crystallized abilities are thus crucial as they can determine (i) the amount of resources available to perform the task and (ii) the amount of resources required by each operation. In other words, to search for information with a search engine, users need to alternatively allocate their attentional resources to updating processes in working memory and information processes. As discussed earlier, current empirical works have provided strong argument on the impact of fluid and crystallized abilities on each of these two components. As a reminder, updating information in working memory heavily relies on fluid abilities and is less demanding if users possess relevant prior topic knowledge or vocabulary skills (Eppinger et al. 2007; Sanchiz et al. 2019b; Sharit et al. 2008, 2015). Processing information (e.g., querying, SERP evaluation, navigation, comprehension processes) is also supported by high level of crystallized abilities such as IS skills or prior knowledge (Hölscher and Strube 2000; Monchaux et al. 2015). In addition, all along the evolution of the activity, processing information in an adapted way can be improved by high level of fluid abilities (Dommes et al. 2011; Sharit et al. 2008, 2015).

In this chapter, we discussed how lower levels of fluid abilities can also alter information processing by increasing exploitation and reducing exploration strategies (Chin et al. 2015; Sanchiz et al. 2019b). Overall, low fluid abilities tend to increase the cost in cognitive resources of information processes as early as the initial stage of the activity (Sanchiz et al. 2017b). They also cause difficulties for the stages that particularly require refreshing in both memory processes and information processes (such as the evaluation stage or regulation processes Sharit et al. 2008, 2015). For instance, a larger proportion of exploitation strategies on SERP evaluation and query reformulation could appear for users with lower fluid abilities. Regarding crystallized abilities, research has shown that the more users possess prior knowledge, vocabulary skills or IS skills, the lesser costly in cognitive resources information processes are. For instance, high knowledgeable users need fewer resources to produce a relevant initial query, to select relevant websites or reformulate (Hölscher and Strube 2000; Sanchiz et al. 2017a, b; Vakkari et al. 2003). Consequently, by lowering the cognitive costs of information processes, crystallized abilities can contribute to increase the amount of resources available for the task. In this way, they may facilitate the allocation of resources to refreshing in working memory processes and processing alternatively.

In general, our framework also includes the distinction between exploration and exploitation strategies in the information processing component of IS. As represented in the lower frame of Fig. 5.2, deeper processing and information integration (i.e., right branch of the frame) correspond to exploitation behavior. In these stages, users engage in comprehension processes to extract relevant information and integrate them into their mental model. The left branch (regulation and adaptation strategies) along with the gray arrows corresponds to exploration strategies (i.e., elaboration of new search paths through reformulation or selection of new website) and regulation stages.

5.5.2 Challenges and Perspectives for Future Works

Future works should deeper investigate how both components of IS are impacted by fluid and crystallized abilities when the search task actually serves a specific goal (such as writing an essay in an educational setting). In such contexts, users' attentional resources are particularly solicited by refreshing in working memory processes. Indeed, on a theoretical plan, the framework introduced may also explain why users with lower fluid and crystallized abilities can particularly have difficulties when the search task is conducted in parallel with another task. Conversely, such context may affect the amount of resources available for information processing and the trade-off between exploration and exploitation strategies (i.e., causing, for instance, too much irrelevant exploitation or shallow exploitation of the sources of information accessed).

Another challenge to be investigated for future works is the investigation of the final stage of the activity. Indeed, predicting when and why users stop searching for information (particularly in cases when they do not solve their search need) is a key leverage to understand their difficulties and develop useful IS support tools. To do so, we argue that pursuing the analyses of the different stages of the activity could help research better monitor users' difficulties.

Implications of this new framework provide insights on how to design useful support tools for users with particular needs. Indeed, our framework argues that IS support tools should not just attempt to cope with the decrease of attentional resources caused by lower fluid abilities (such as decreasing the amount of information on the screen or providing query suggestions) but should:

- Reduce all along the activity the amount of parallel processing (i.e., refreshing in working memory and information processing) to help users refresh information and elaborate adapted exploration and exploitation strategies.
- Support the alternative allocation of attentional resources between refreshing and information processing components. For instance, such tools could consist in metacognitive crutches that would help users keep active their search goal in working memory.

As an illustration, a study by Sanchiz and her collaborator (2019b) showed that a search interface designed to support the alternative allocation of resources to update in working memory and information processing could help older adults display more flexible search strategies. Displaying users' query at all time during the search (i.e., allowing users to have a glance at their current sub-goal at all time and at low cognitive costs) can help older adults evaluate information on content pages and reformulate new queries at lower cognitive costs. Such example shows how the framework introduced in this chapter can help the design of better system or search interface. Additionally, training users to strategically allocate resources to the two components of IS (i.e., update in working memory and information processing) could improve the search strategies and performance of users with lower fluid and crystallized abilities. Such training could also cope with the constraints of complex IS contexts.

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