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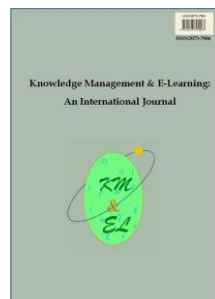
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Exploring patterns in undergraduate students' information problem solving: A cross-case comparison study

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Abstract: Students today routinely conduct research in the digital world to solve problems in daily life and in learning tasks. Although research to date has proposed different models to describe the processes of information problem solving (IPS), little is known about the cognitive patterns demonstrated in the processes, particularly the iterative nature of IPS and the driving factors behind iterations. The current study employed the lens of a self-regulated problem-solving model to develop an in-depth understanding of learners' IPS processes. Analysis and cross comparisons of three students' on-screen research activities, think-aloud articulations, artifacts, and interviews revealed three representative patterns for performing an IPS task: reasoning-driven, prior knowledge/task-driven, and information-driven. These different patterns manifest qualitative differences in the three students' research behaviors and iterations of problem-

solving stages. The findings afford an in-depth understanding of the cognitive dimension of IPS, and yield important implications for scaffolding learners in effective IPS.

Keywords: Problem solving; Information problem solving; Ill-structured problem solving; Information literacy

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1. Introduction

The importance of information literacy is shown by its appearance in the standards at all levels of education (e.g., Association of American Colleges and Universities, 2007; Partnership for 21st Century Skills, 2006). American Library Association (2000) defines information literacy as the knowledge and skills that enable an individual to recognize the

need for information, and to effectively search, evaluate, and use information. Eisenberg and Berkowitz (1992) approached information literacy from the problem-solving standpoint, which they termed as information problem solving (IPS) and prescribed the Big 6 model to train IPS in six steps: task definition, information seeking strategies, location and access, use of information, synthesis, and evaluation.

Building on the works by Eisenberg and Berkowitz (1992), Brand-Gruwel, Wopereis, and Vermetten (2005) decomposed the cognitive skills required in IPS and derived a descriptive model, which they later validated in the context of IPS with the Internet (Brand-Gruwel, Wopereis & Walraven, 2009). The model describes five iterative phases of IPS: define the problem, search information, select information, process information, and present information; overarchingly, Brand-Gruwel et al. (2005) argue that the five phases are coordinated by such regulation activities as orientation, steering, monitoring, and testing.

Research has been conducted to examine factors or strategies associated with IPS. From the perspective of information seeking, Nachmias and Gilad (2002) identified three sets of strategies: search engine strategies (e.g., Boolean search), browsing strategies (e.g., using a directory), and direct access strategies (e.g., directly typing the URL of a website). From a more cognitive perspective, Hill and Hannafin (1997) identified five key factors that influence IPS: metacognitive knowledge, perceived orientation, perceived self-efficacy, system knowledge, and prior subject knowledge. Building on prior research, Tsai and Tsai (2003) proposed a more comprehensive framework that categorized IPS strategies into three domains: behavioral, procedural, and metacognitive. While the behavioral and procedural domains encompass strategies for basic web navigation (e.g., orientation/disorientation, trial and error), metacognitive domain involves strategies such as purposeful thinking, selecting main ideas, and evaluating information (Tsai & Tsai, 2003).

Further research has also been carried out to examine how experts perform differently from novices in IPS processes. Brand-Gruwel et al. (2005) found that PhD students spent more time than college freshmen on problem definition at the beginning of an IPS task. However, learners across all levels spent relatively little time on problem definition (Brand-Gruwel et al., 2009). Zhou (2013) found that high IPS performers used more queries and spent more time on web searching, reading information, and reviewing IPS task questions, whereas low performers started answering IPS questions much earlier. Further, high performers engaged more in regulation activities (Brand-Gruwel et al., 2005; Brand-Gruwel et al., 2009; Zhou, 2013). Jointly, research has pointed out the need for novices to develop stronger self-regulation and more metacognitive awareness to facilitate IPS (Tabatabai & Shore, 2005; Zhou & Lam, 2019). Accordingly, researchers designed and investigated interventions to develop learners' IPS expertise, using such approaches as embedded instruction, question prompts, expert modeling, or regulation feedback (Argelagos & Pifarre, 2012; Frerejean, van Strien, Kirschner, & Brand-Gruwel, 2018; Frerejean, Velthorst, van Strien, Kirschner, & Brand-Gruwel, 2019; Gagnière, Bétrancourt, & Détienne, 2012; Raes, Schellens, De Wever, & Vanderhoven, 2012; Timmers, Walraven, & Veldkamp, 2015; Yuan, Wang, Kushniruk, & Peng, 2016).

Although IPS research has been fruitful in identifying constituent phases, exploring expert-novice differences, and experimenting instructional approaches, research to date has mostly focused on performance groups as units of analysis, and relied on quantifying think-aloud or log data, such as time and frequencies, for the purpose of drawing convergent patterns for a given group. Less attention has been paid to individual learners as to how they define a problem or how they move towards the

solution. As a case in point, when a learner embarks on an IPS task, problem definition “will always be performed at the beginning of the process” (Brand-Gruwel et al., 2009, p. 1208). However, this initial problem definition is subject to change, when the learner tries a new query or revisits the IPS task description for a closer look (Zhou, 2013). Although Brand-Gruwel et al. (2005) contend that the five IPS phases are iterative, and explain the updates of problem definitions through learners’ regulation behaviors, it is unclear *how* learners’ problem definitions, or their internal models of an IPS task (Lazonder & Rouet, 2008), iterate over time, how learners act on their evolving problem definitions, and more importantly, what drives the iterations. A closer examination of the iterations and underlying impetus in individual IPS processes can provide a divergent perspective on the cognitive processes in IPS, which bears important implications for teaching or facilitating effective IPS. To better understand the iterations in IPS, we turn to the literature on ill-structured problem solving, which conceptualizes problem solving as a process in which problem solvers construct, manipulate, and test their mental representations of problems (Jonassen, 2004).

Ill-structured problems are problems with unclear elements, multiple solutions, paths, and evaluation criteria (Jonassen, 1997, 2000). They are distinguished from well-structured problems that have clearly defined initial and goal states, and can be solved by following step-by-step procedures. An individual cannot begin to try to solve an ill-structured problem until he or she understands it (Simon, 1978). Voss and Post (1988) suggested that ill-structured problem solving involves two phases: problem representation and problem solution. In solving ill-structured problems, deep and schematically organized knowledge structures enable solvers to isolate essential patterns and relations in a problem (Hmelo-Silver, Marathe, & Liu, 2007), negotiate multiple causal paths, and identify and apply domain principles with flexibility (Tawfik, Law, Ge, Xing, & Kim, 2018). However, when domain knowledge is lacking, solvers often rely on self-regulative strategies to facilitate ill-structured problem solving, as they monitor and reflect on progresses, errors or difficulties, and revise their approaches accordingly (Glaser & Chi, 1988; Hong & Choi, 2011).

To capture the complexity of ill-structured problem solving and highlight the integral and interweaving presence of self-regulation in the process, Ge, Law, and Huang (2016) proposed a self-regulated, ill-structured problem-solving (SR-PS) model, which depicts the problem-solving process in two iterative stages: problem representation (PR) and solution generation (SG). When encountering a new problem, problem solvers actively engage in self-regulated processes between PR and SG, in order to generate a solution (Ge et al., 2016). In the stage of PR, a problem solver analyzes, interprets, and develops an understanding of a problem (Jonassen, 1997). In the IPS context, PR is the stage where the problem solver articulates and analyzes an IPS task, recalls relevant knowledge, identifies information needs and task components, and formulates problem-solving goals. PR is critical in ill-structured problem solving, because once a plausible PR is established, it feeds and serves as input into the subsequent stage - SG, where the problem solver identifies tools and resources, and applies relevant knowledge, strategies, and procedures to generate a viable solution. In the IPS context, SG is the stage where the problem solver, based on the present PR, identifies search tools and query terms, conducts information search, evaluates information, and integrates information for a feasible solution.

Importantly, ill-structured problems can rarely be solved in one single PR-SG iteration. The SR-PS model highlights the iterative navigations between PR and SG, through problem solvers’ self-regulated processes of evaluation, justification, and reflection (Ge et al., 2016; Kitchner, 1983). While at the SG stage, if problem solvers

judge the current solution to be inadequate, they may return to PR to identify additional task components or information needs, which initiates another round of PR-SG. In the case of IPS, if problem solvers, upon reflection, feel that the current solution does not sufficiently address the IPS task, then they may revisit and update their PR. The PR-SG iterations continue until the problem solver deems that a satisfactory solution is reached.

The literature on ill-structured problem solving provides an insightful lens to examine IPS. First, past IPS studies had not paid sufficient attention to the distinction between ill- and well-structured tasks. A well-structured IPS task (e.g., finding out the tallest building in the world) and an ill-structured one (e.g., finding out the relationships between psychological factors and stress) require different problem-solving strategies (Laxman, 2010; Wopereis, Brand-Gruwel, & Vermetten, 2008). As such, it would be more meaningful to separately examine how learners approach ill-structured IPS tasks. Second, the SR-PS model (Ge et al., 2016) provides a framework to analyze and understand learners' evolving problem definitions and ensuing solutions as they perform an ill-structured IPS task. In light of the literature, we sought to use problem solvers' evolving PR-SG's as anchors to examine IPS, in order to better understand the nature of iterations in IPS. We asked the following research questions:

- How do learners' problem-solving stages (PR-SG's) iterate throughout the process of solving an information problem?
- What are possible triggers behind the iterations?

2. Method

2.1. Participants

Nine undergraduate students from a U.S. southeastern university voluntarily participated in the study through informed consent. The students, aged 20-25, were juniors or seniors in an information technology program. Although their years of using modern technology might vary, all the participants previously took and passed an information literacy course in their curriculum that taught online information search. Further, in completing the first two years of their program, the students had been exposed to various modern technologies, and had to conduct online information search regularly. Thus, the participants generally had reasonable levels of technology skills through their coursework.

2.2. Settings and data sources

The students were individually invited to a session with one of the researchers. All the students were in a good health condition at the time of their respective session. The session took place in a meeting room at the university. The researcher first informed students the purpose and procedure of the session. Next, thinking aloud was introduced to students, followed by a brief training (Ericsson & Simon, 1993). The purpose of the training was to help participants understand thinking aloud and become comfortable in verbalizing their thoughts while performing the IPS task. Specifically, the researcher informed the students, "Please think out loud during the process, that is, speak out loud everything that comes to your mind. Please keep constantly talking from beginning till the end of the task." The participants then performed a practice online search task, while thinking out loud at the same time. The training concluded when a student was observed becoming comfortable talking out loud.

After introducing thinking aloud, students were asked to open and read the IPS task document (Appendix A) on a laptop computer, and then proceeded to work on the task. The task, which was adapted from Brand-Gruwel et al. (2005), asked students to take on the role of a columnist for a consumer's magazine to write a one-page response to readers' questions: *How to deal with food that is expired? Can we continue to eat them?* To accomplish the task, students had to conduct online research to identify information needs, search, extract, and evaluate information, and integrate information in their written responses. The IPS task was chosen due to its complexity, ill-structured nature, and multiple paths/solutions. Students could approach the task from different angles, depending on the interpretation of the problem. For example, how does one define expiration? What is considered edible? The complexity of the problem could increase when one considers, for instance, do food types matter? Is food storage a factor to consider? Each angle can lead to different answers. There was no time limit for students to complete the task. They could take as much time as needed, and stop only when they felt the task was completed. The same researcher conducted all the think-aloud sessions. Throughout the process, the researcher was in the same room but maintained a comfortable distance to minimize potential stress for the students. The only time when the researcher would interfere was when a student stopped talking, in which case the researcher would display a "Keep on talking" sign to remind the student.

Data were collected from three sources. First, students' real-time on-screen activities, both Internet research and writing, as well as their think-aloud articulations throughout the IPS process were recorded using *Camtasia*, a screencasting tool. The recording was non-intrusive, only operating at the background of the computer. The duration of the recordings ranged between 18 and 73 minutes, with an average of 41 minutes. Second, students' final written responses were collected. Third, a semi-structured interview immediately followed the IPS task to further understand each student's research process and clarify any questions from the observation of the process.

2.3. Data analysis

A team of five researchers participated in the data analysis. Three members closely analyzed and coded the data, both separately and as a group to discuss, reconcile, and reach consensus. The data along with coding were then critically reviewed by the other two members, which often prompted further discussions, analyses, and revisions.

Data analysis was conducted in two stages. Within-case analysis was conducted first to examine IPS processes at the level of individual students. Each student's recorded on-screen activities (Internet research and writing) and transcribed narrations were juxtaposed, closely reviewed, and open-coded to identify key event segments within the case (Miles, Huberman, & Saldaña, 2014). The student's written response and interview data were triangulated whenever needed. Next, the segments were reviewed and coded using the SR-PS framework (Ge et al., 2016), which was elaborated earlier in the Introduction section. Specifically, the data were coded according to the SR-PS model's two iterative problem-solving stages: problem representation (PR) and solution generation (SG). As an example, upon reading the task questions, "*How to deal with food that is expired? Can we continue to eat them?*" - when a student stated that the answer "really depends on *the kinds of food* you are talking about," she was engaged in representing or framing the problem from a particular angle - kinds of food. In this case, the segment would be coded as a PR. If the student subsequently started to describe specific food types that are okay or not okay to eat past expiration, then she was suggesting a solution based on her current PR - the suggested solution would then be

coded as an SG. As another example, in reviewing Google search results, if a student started to pay attention to the names of different food expiration dates, then the student was formulating his problem definition from the angle of different food dates, which would be coded as a PR. Subsequently, if, based on the PR, the student started to name and describe different expiration dates in writing, then he was composing a solution, which would be coded as an SG. All students had more than one set of PR-SG in their IPS processes. Hence, each student's PR's and SG's were coded numerically as PR1, PR2 ... or SG1, SG2 ..., in a chronological order. Driving factors behind the iterations (e.g., the impetus behind the transition from SG1 to a new PR2) were iteratively and hermeneutically drawn, discussed, and refined by the researchers, from both emic and etic perspectives.

Upon establishing an in-depth understanding of individual students' IPS processes from within-case analysis, the researchers conducted the second stage of data analysis - cross-case comparisons which focused on examining IPS processes across different cases (Creswell, 2007). The comparisons sought to identify commonalities within the cognitive process of IPS, but more importantly, differences in iterations and underlying drives that set different cases apart. In the process, the researchers often had to revisit and refine within-case analysis. The iterative process continued until salient themes emerged in the comparisons.

To address the research questions, we used the two foci in the research questions (i.e., iterations of problem-solving stages, and triggers behind the iterations) as anticipated lenses, and employed a replication logic approach (Yin, 2018) to compare the cases through the selected lenses. When an important finding was identified from a single case (student), we sought similar or contrasting findings from other cases. In serving the purpose of this study, which is to provide a divergent account of IPS processes, the replication logic yielded three cases that uniquely represent different IPS patterns and the triggers behind them. Specifically, the three identified cases demonstrated qualitatively distinct problem-solving iterations (PR-SG's), which were driven by the differential weight the student in each case placed on the factors uncovered from the data analysis. In the next two sections, we report and discuss findings, beginning with within-case iterations and themes, followed by cross-case comparisons.

3. Within-case iterations and themes

In this section, we report findings within the three individual cases: Lisa, Calvin, and Tom. The students in all three cases indicated in follow-up interviews that they had some prior knowledge about handling expired food, but the knowledge was only based on their personal experience, casual readings, or informal conversations; none of them had any formal knowledge about the topic.

In reporting each case, we first provide an overview of the problem solver's IPS process and a description of the final product (i.e., the written response). We then detail the PR-SG iterations identified in the case, followed by the key themes drawn from the case. It should be noted that the quoted students' verbalizations in the report, unless explicitly specified the follow-up interview as the data source, were all extracted from students' real-time think-aloud data. An overview of descriptive statistics for the three cases are provided in Table 1.

Table 1
Descriptive statistics of the three IPS cases

	Lisa	Calvin	Tom
Duration	18 min	39 min	34 min
Queries & information use	6 queries 3 web pages Minimal use	1 query 4 web pages Used 2 pages	7 queries 7 web pages Used 6 pages
Final written solution	206 words 3 key ideas, with inaccuracies	292 words 2 key ideas, with inaccuracies	471 words 4 key ideas

3.1. Case 1: Lisa

3.1.1. Overview of Lisa's IPS

Lisa completed her task in less than 18 minutes, the shortest among all the nine participants in the study. Altogether Lisa performed six Google queries. She opened three web pages in four very brief occurrences, each lasting 2-14 seconds. Lisa spent minimal time on Google queries, search results, or web pages, totaling about 73 seconds. Her written response was mainly generated from her prior knowledge.

3.1.2. Lisa's final written response

Lisa's final written response has a total of 206 words. Her response shows a recognizable structure of three key ideas. The first idea is, "... expired food may be ok to consume based (on) what kind of food it is." The idea is followed by a description of a few food types and their different handlings. The second key idea is the meaning of three types of food dates (expiration dates, best-by, and use-by). The third idea is the handling of expired food - either tossing out or composting.

There were a few inaccuracies in Lisa's response. For example, she wrote that "'Use-by' dates are synonymous with expiration dates." However, *if* she read the source she chose not to open, it suggested that use-by dates solely indicate freshness, a way in which food manufacturers convey when a product is at its peak. In another instance, Lisa wrote, "Canned foods are explicitly not to be consumed after their expiration date to prevent botulism toxin poisoning." In support of this argument, she pasted the URL of a web page. Yet, the web page explicitly stated that botulism is associated with home-canned foods, which do not have labelled expiration dates like those from grocery stores.

3.1.3. PR-SG iterations throughout Lisa's IPS process

Upon starting the IPS task, Lisa wrote the title in her response, "What to do with expired food." Instantly, she verbalized her understanding of the task, "It really depends on the kinds of food you are thinking about" (PR1). Although she did a Google query with the task question, *What to do with expired food*, Lisa did not read any query results, but instead started to develop her own solution in writing. Drawing on her prior knowledge,

she described those food types that “may be ok to consume” after expiration such as bread, crackers, processed food, and those that are “not a good choice to consume,” such as meats, seafood, vegetables, fruits, dairy foods (SG1). Appearing in a need to learn more about the “ok to consume” foods, Lisa went back to Google search with the second query, *foods that are ok to eat after expiration date*. This time, she scanned the search results quickly but, again, did not open any webpage, although the search results did show sources that could address her query. Instead, while scrolling down the search results, Lisa paused in the middle of the page where Google featured a “People also ask” section, and got interested in a featured question, “what does the best by date really mean?” She expanded the collapsed question and quickly read the short answer underneath. Verbalizing that “[best-by date] is also I think can take into consideration” (PR2), Lisa went back to her response and paraphrased what she had just read, “Expiration dates are not to be confused with ‘best by’ dates because best by dates are only an indicator of when the product will taste at its best.” Appearing as an intention to seek help in contrasting expiration dates with best-by dates, Lisa went back to the same search results page. This time, Lisa read another question in the same “People also ask” section, “What does it mean use by date?” However, she did not click to read the answer at all, but instead returned to write her own idea, “‘Use by dates’ are synonymous with expiration dates.” Taken together, Lisa’s SG2 focused on different dates for food.

Next, Lisa decided to revisit the task description. Upon reading, she adjusted the focus of the task to “... ways to deal with food after it’s been expired” (PR3). Subsequently, she did another Google query, *How to deal with food past its expiration date*. Following the same pattern as her previous queries, she did not review any search results or webpage, but went directly back to her response and described two ways to deal with expired food (SG3): “... in most cases, the only option is to throw it out ... However for a more ‘green’, environmental approach, certain food ... can be put into compost.”

In writing about composting expired food, it occurred to Lisa that canned food was a type of food that cannot be put into compost. The thinking about canned food prompted Lisa to realize that she did not include this particular food type in her earlier writing about the food types that are (un)safe to eat after expiration. Hence, she travelled back to her previous PR1-SG1 - returning to the first paragraph of her response, Lisa added canned food to the “not a good choice to consume” list: “Canned foods are explicitly not to be consumed after their expiration date to prevent botulism toxin poisoning.” It is worth noting that the contention about canned food did not come from online research, but from Lisa’s own idea instead - although she did a Google query, the purpose was only to look up the name of the specific toxin, botulism, for use in her writing.

Lisa revisited the task description the second time, this time focusing on the writing requirements (PR4). She spent the last 5.5 minutes on fulfilling the requirements (SG4). Specifically, Lisa noted the requirement to “use the information from the Internet to build your argument,” and questioned herself, “Does this mean I have to cite sources?” After a long inhale, she stated, “Just to be safe,” and then worked to insert the URL’s of three web pages into her response. For those three pages, Lisa either directly copied the URL of a page without reading at all, or skimmed a page very briefly just to verify that its content pertains to her writing. Lisa ended her task with minor editing. The iterations of Lisa’s IPS process are illustrated in Fig. 1.

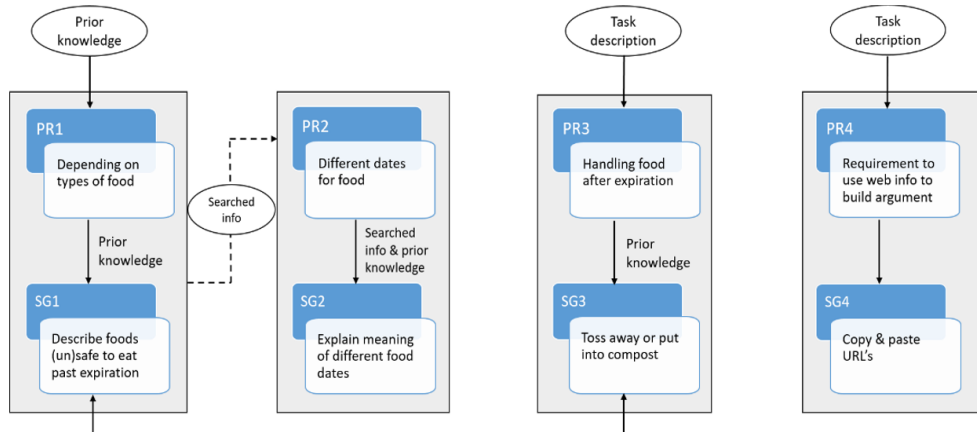


Fig. 1. Lisa’s PR-SG iterations throughout her IPS process (dotted arrow denotes a lack of logical/progressive relationship between linked PR-SG iterations; double-headed arrow denotes navigation between different PR-SG iterations)

3.1.4. Within-case themes in Lisa’s IPS

The most striking theme in Lisa’s case was the minimal time she spent on information search. Even when she did an online search, she either did not read search results at all, or quickly skimmed the results, or, in the rare cases when she did open a page from search results, skimmed the page only to verify that she could copy its URL to include in response. As such, her PR’s were rarely driven by new information from search, except in one case when she serendipitously came across information from the “People also ask” section on Google, not from the results of an intentional search. On the other hand, Lisa’s IPS was heavily driven by her prior knowledge. Her PR1 was immediately drawn from prior knowledge. Since she rarely relied on information from research to formulate her response, her SG’s were also largely relied on her prior knowledge. However, as described earlier, her prior knowledge was not always accurate, but she did not show any attempt to verify her ideas.

Lisa was also keen on meeting task requirements. Attempting to perform as a “good” student by school norms, she consciously revisited the task twice trying to align her effort with the task, each time leading to a new PR. However, in fulfilling the task requirements, she either relied on her prior knowledge without conducting additional research (e.g., PR3-SG3), or copied the URL’s of web pages without actually reading or processing new information (e.g., PR4-SG4). Taken together, although the IPS task requirements were a driving force behind Lisa’s IPS processes, her attempts at fulfilling the requirements were at a superficial level.

3.2. Case 2: Calvin

3.2.1. Overview of Calvin’s IPS process

Calvin spent 39 minutes on completing the task. He performed only one Google query. From the query results, Calvin visited a total of four pages. His response was mostly informed by two of the pages.

3.2.2. Calvin's final written response

Calvin's response has a total of 292 words. There are two recognizable key points in the response: (1) the meaning of different dates for food (e.g., sell-by and best-by); (2) how long different types of foods are edible. There exist some inaccuracies in Calvin's response. For example, only two types of food dates were named in his response, but Calvin later referred to them as "three types," due to a mistake he made earlier in writing. Also, in describing edible time for different food, Calvin listed five bullet points for five types of food: (1) eggs, (2) poultry and seafood, (3) beef and pork, (4) highly acidic foods, and (5) low acid foods. According to the source he referred to in writing, the latter two bullet points (highly acidic foods & low acid foods) both belong to the canned food category which would ontologically align better with the first three bullets. Nonetheless, Calvin listed them as separate categories without making it clear to readers that the last two types are both canned food.

3.2.3. PR-SG iterations throughout Calvin's IPS process

Upon reading the IPS task description, Calvin immediately started to write an introduction in his response by rephrasing the task, "I will explain what we should do with our expired food within this article" (PR1). With this initial understanding of the task, Calvin started to Google *What to (do) with expired food* (SG1). From the search results, he opened a web page, where he found information about different dates for food (e.g., sell-by, use-by). The information prompted Calvin to move from the initial general conceptualization of the task to a specific dimension - dates for food (PR2).

Subsequently, he resumed writing his response by paraphrasing the content on the page. Specifically, he paraphrased the content regarding the meanings of different food dates, agencies who determine the dates, and the fact that milk can last a few days after the sell-by date (SG2). After exhausting what he could use from the web page, Calvin returned to the original Google search results, and opened another linked *WebMD* page "to see if it has anything different." The page, entitled "How long are foods OK to eat," prompted Calvin to approach the task from this new angle (PR3). Similar to what he had done previously, Calvin closely paraphrased the content of the web page in writing, to describe how long different types of food can last (SG3). Afterwards, Calvin visited two other web pages from the initial Google search results, trying to look for "new or more interesting information that we can add in ..." When he believed that the two sources did not offer what he was looking for, he decided to "close our little article here." The task now switched to writing a 1-page response (PR4). Calvin spent the last 10 minutes writing a conclusion, compiling, and proofing the response (SG4). The iterations of Calvin's PR-SG are illustrated in Fig. 2.

3.2.4. Within-case themes in Calvin's IPS

What is unique about Calvin's case is that he let the searched information drive his IPS process, whereas his own reasoning was lacking. The lack of reasoning was reflected at two levels. At a *macro* level, Calvin did not have a clear idea what kind of information could potentially contribute to a solution, and employed a lower-level criterion of "something new/different/interesting" in searching for information. As such, his PR2 and PR3 were both driven by the new information found on web pages, which led to the two key ideas in his solution. At a *micro* level, Calvin did not show sufficient reasoning and internalization in processing the new information from his search. He did not read through a page or a portion of a page to establish a sufficient understanding before

writing. Instead, he read one, or very few, sentences and immediately paraphrased the sentence(s) in writing. The lack of reasoning at this micro level is likely the reason behind the aforementioned inaccuracies in his response.

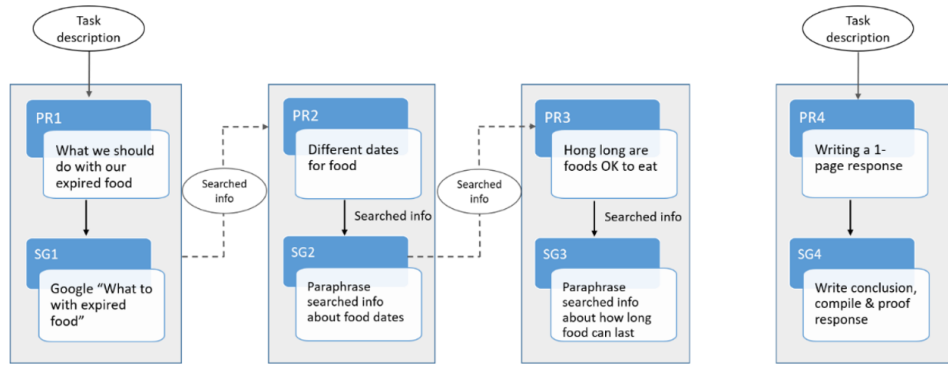


Fig. 2. Calvin’s PR-SG iterations throughout his IPS process (dotted arrow denotes a lack of logical/progressive relationship between linked PR-SG iterations)

3.3. Case 3: Tom

3.3.1. Overview of Tom’s IPS process

Tom spent 34 minutes in completing the task. He performed a total of seven Google queries. From the query results, Tom visited seven webpages, six of which he referred to in gathering or confirming ideas for his written response.

3.3.2. Tom’s final written response

Tom’s written response has a total of 471 words. In his writing, Tom made four key points: (1) a great amount of wasted food is still safe to eat despite expiration, (2) distinguishing sell-by date from expiration date, (3) methods to identify spoilage in different types of food, and (4) ways to properly store food to prevent spoilage.

3.3.3. PR-SG iterations throughout Tom’s IPS process

Upon reading the task, Tom started to write a title of his response, “What to do with expired food,” and immediately recalled that he had read a relevant news article about “feeding college students expired food without them knowing for an experiment,” which implicitly suggested that Tom was generally aware of the safety of expired food (PR1). He subsequently did a Google query to locate and read the article, based on which Tom later wrote the introduction of his response, “... 40 percent of food in the US goes to waste each year, despite the fact that much of it is still safe to eat” (SG1).

In seeking “something on actual expiration dates” (PR2), Tom performed a Google query, *Expiration dates how long after*. From the search results, Tom visited a *WebMD* page, the same page Calvin read in his search. From the page, Tom read about the meanings of different dates for food (e.g., sell-by date). Returning to his response, Tom synthesized the information in writing to clarify the meaning of sell-by dates, their

difference from expiration dates, and the fact that food past sell-by dates is still safe to eat, only with a lower quality (SG2).

Returning the *WebMD* page, Tom continued to read a section on “How long are foods OK to eat” for different types of food (e.g., eggs, poultry and seafood, beef and pork, and canned goods). While reading that “cans bulging with bacteria growth should be discarded, no matter what the expiration date,” Tom was prompted with a new idea, and immediately returned to his response to start a new paragraph, “When dealing with preserved food such as canned foods, bulging can be a sign of bacteria growth ... this can occur even before the can’s labelled expiration date.” Tom was unsure where the new writing would fit in his solution, but just “write this down so I’ll remember it later... and decide later.” It is clear that while Tom was engaged in the cycle of PR2-SG2, he was prompted with the prospect of a new PR, but he chose not to pursue at the moment.

After reading more from the *WebMD* page, Tom felt the “need to review my task information, because I don’t remember quite what’s relevant.” Upon revisiting the task description, Tom questioned himself, “I think the bigger question is, what’s the definition of it (expiration). Does it mean past marked dates, or is it safe to eat after spoilage started, which would be wrong?” It appeared that the revisiting of the task description and his reflection on it affirmed Tom of his PR2-SG2, which was to view the task from the lens of different food dates, and distinguish expiration dates from other labelled dates. While still operating within the same PR2-SG2, Tom continued to read the rest of the *WebMD* article, during which he performed two key actions. First, he noted some new information, regarding the use of senses to determine whether food is fresh (e.g., sniffing milk). Similar to how he treated the previous information about bulging food cans, Tom noted the information but opted not to pursue it until later. Second, Tom performed two additional queries, both within his current PR2-SG2: *food expiration dates chart* and *food waste expiration*. Triangulating the newly searched information with what he had already written, Tom added two more pieces of information in writing to strengthen his SG2.

At this point, Tom turned his attention to the two points of information that he chose not to pursue earlier: the information about bulging cans he recorded previously, and the recommendation of using senses to determine food freshness. The two pieces of information converged to give Tom a clear new idea, which he wrote, “When dealing with ‘expired’ food, using common sense and senses is the best method to determine if food is still safe to eat” (PR3). Tom then went on to describe ways to identify spoilage for specific types of food (SG3). Canned food, which he previously wrote about, was described first. He then added the sniffing method as a way to identify spoiled milk. At this point, Tom questioned himself, “How do you deal with eggs? Do you have to shake them?” To find out the answer, he did another Google query, compared two alternative methods from the search (place egg in water vs. shake it), and returned to describe one method - “the water method, coz it’s more reliable.” It is worth noting that Tom did not go straight to read about the water method. Instead, he started by asking himself, “Is it the good or the bad egg that can float? I believe it would probably be ... the bad eggs since the bacteria would be creating gas.” Further reading confirmed Tom’s hypothesis. After describing the water method to identify spoiled eggs, Tom continued with one more Google query and enriched his SG3 with more information.

After describing ways to identify spoiled food, Tom realized that he needed to discuss a logically related topic, “I need to talk about preserving food. I haven’t talked about preserving food” (PR4). Subsequently, he did another Google query. Based on the searched information, he wrote about proper storage conditions of different food products (SG4). While in the process, he also revisited the first news article he read at the

beginning, and used some new information to reinforce his SG1. Tom’s PR-SG iterations are illustrated in Fig. 3.

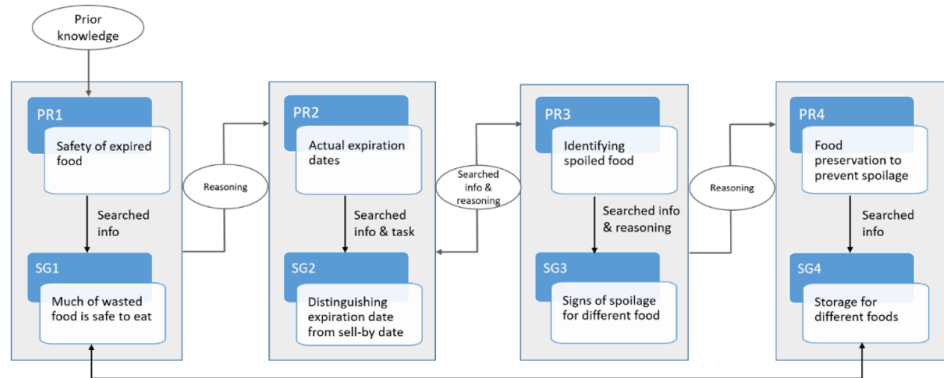


Fig. 3. Tom’s PR-SG iterations throughout his IPS process (solid arrows between PR-SG phases denote reasoning-triggered iterations; two double-headed arrows denote navigations between different PR-SG iterations)

3.3.4. Within-case themes in Tom’s IPS

A clear thread that ran through Tom’s entire IPS process was his reasoning. At a broader level, most of Tom’s PR-SG iterations were driven by his reasoning. For example, after presenting a general idea that much of wasted food is still safe to eat (SG1), Tom decided to focus specifically on “actual expiration dates” (PR2). In the process of distinguishing expiration dates from other labelled dates (SG2), Tom noted new pieces of information which later converged to formulate his PR3 (identifying spoiled food). After describing signs of spoilage for different food (SG3), Tom realized the “need to talk about preserving food” (PR4). It appears that Tom’s reasoning and associated mental schemes guided his problem-solving process.

At the level of individual PR’s, Tom’s reasoning also guided his development of corresponding SG’s in his search, verification, and synthesis of information. For example, after describing how to identify spoiled canned food and milk, Tom realized the same need for other food types such as eggs, and conducted additional queries to actively search for answers. In reading the use of water method to identify spoiled eggs, Tom made his own hypothesis before finding out whether good or bad eggs would float in water. He was not merely led by new information, but used reasoning to interpret and search for new information.

4. Cross-case comparisons

In this section, we report and discuss the second part of the findings, which are comparisons across the three representative cases reported earlier. We start by discussing commonalities in the iterations that took place in the three IPS processes, which addresses the first research question on how learners’ problem-solving stages (PR-SG’s) iterate in IPS. Next, we address the second research question, which is about triggers behind PR-SG iterations and how the emphasis on different triggers is reflected in qualitative differences across the three cases.

4.1. Commonalities in IPS iterations

In all three cases, the students showed all the IPS components outlined in Brand-Gruwel et al. (2005): define the problem, search information, select information, process information, and present information, along with regulation activities. Interestingly, in a log-analysis study, Zhou (2013) found that students in the low-performing group started answering IPS questions in writing much earlier than those in the high-performing group, whereas all three students in this study started writing their response early in the process. One may argue that all of the three students might belong to the low-performing group, but the three individual IPS processes reported above may suggest other plausible reasons. In all three cases, the students started working on their responses right away (e.g., a title or introduction sentence) and continuously went back and forth between conducting research and writing the response. It is plausible that the starting time to write a response may not be an ideal indicator of different performance groups. Rather, the writing might have served as a mechanism to offload part of limited-capacity memory, so that the students could focus on cognitively more demanding IPS processes such as problem definition or reasoning (Lajoie & Azevedo, 2000; Sweller, van Merriënboer, & Paas, 1998).

Using the PR-SG lens suggested by Ge et al. (2016) to examine the IPS process, we found that all three cases went through four iterations of problem definitions, or PR's, and acted upon each problem definition accordingly (SG). Three common themes emerged in the iterations. First, beginning PR's tended to be more general, and later iterations became anchored on specific dimensions. For example, Calvin's PR1 was a general question, "What we should do with our expired food." As the iterations proceeded, the PR's in all three cases became more specific, focusing on different aspects (e.g., different dates for food, identifying spoiled food). Although previous research highlighted the iterative nature of IPS (Brand-Gruwel et al., 2005), the finding provides clear evidence for the iterations and their progressive trends.

Second, the loci of PR's in the IPS processes were not limited to the problem itself (i.e., how to handle expired food), but could go beyond into the realm of IPS task requirements, which are not directly related to the problem to be solved. In two of the cases (Lisa and Calvin), the PR's at a later stage became more centered on satisfying interpreted IPS task requirements. For example, Lisa's PR4-SG4 focused on locating and pasting URL's of web pages to satisfy her interpreted requirements of the IPS task; Calvin spent more than a fourth of his time on editing and finalizing the 1-page written response to meet his understanding of the task requirements. Although previous studies identified a variety of behavioral, procedural and metacognitive factors that influence IPS (Hill & Hannafin, 1997; Tsai & Tsai, 2003), task requirements, an essential component in the learning context, are often ignored. The finding suggested how task requirements might shape IPS processes.

Third, although the PR-SG iterations could clearly be distinguished from one another in all three cases, which suggests an overarching progressive trend, the students sometimes traveled back and forth between iterations. For example, while working on her SG3, Lisa travelled briefly back to strengthen her SG1 (as shown in the large, double-headed arrow in Fig. 1). Similarly, as Fig. 3 shows, Tom also visited *back* his SG1 while working on SG4; conversely, while still working on his SG2, Tom also moved *forward* to formulate an emerging PR3. The finding further substantiated the nature of iterations in IPS processes.

While the above themes represent commonalities in IPS iterations found in the study, the iterative patterns in the three cases were in fact qualitatively different, largely due to the triggers behind the iterations, which we discuss next.

4.2. Triggers behind qualitatively different iterations

From the three cases, we see four key triggers that were at play in the IPS process: (1) prior knowledge, (2) searched information, (3) students’ reasoning, and (4) IPS task requirements, which are not directly related to the problem to be solved. The four triggers had differential levels of influence on the three IPS cases, which led to qualitative differences in their PR-SG iterations. Table 2 provides a summary regarding the roles of the four factors in the three IPS cases.

Table 2
Roles of four key factors in the three IPS cases

Factors	Lisa (Prior knowledge- and task-driven)	Calvin (Information- driven)	Tom (Reasoning-driven)
Prior knowledge	Over-reliance despite inaccuracies	Minimal use	As a reference that is subject to verification
Searched information	Minimal	Over-reliance	Filtered through reasoning
Reasoning	Focusing on the negotiation between prior knowledge and task demands	Focusing on identifying something new or interesting	Coordinating force to identify and bridge the gap between current solution, new info, task, and prior knowledge
Task requirements	Eager to fulfill, but superficially	Fulfill with due effort	Ensure alignment with solution

In the case of Lisa, we see her over-reliance on prior knowledge, despite inaccuracies in her understanding. Further, Lisa was very task-oriented and keen on satisfying IPS task requirements, although she worked to meet some requirements in a superficial manner. On the other hand, Lisa made minimal use of new information, and her reasoning was mainly focused on the negotiation between the task demands and her prior knowledge. Taken together, the two factors, prior knowledge and task requirements, became key driving forces behind Lisa’s PR iterations and corresponding SG’s. As a result, Lisa’s IPS iterations tended to be discrete and additive, lacking logical and progressive relationships with one another.

Compared with Lisa’s IPS, Calvin’s was far less influenced by his prior knowledge. On the contrary, he relied heavily on searched information, which drove his iterations. In using the searched information, Calvin’s reasoning remained at a low level, aiming only to find new or interesting information to add to the current solution. The resulting IPS iterations are still additive and discrete, similar to Lisa’s, lacking logical and progressive relationships.

Tom appeared to be the most balanced among the three cases concerning the roles of the four factors in his IPS process. Tom did apply his prior knowledge, but he used the knowledge as a frame of reference that was subject to verification. As a case in point, although Tom and Calvin referred to the same website as a key information source, Tom did not take the new information at its face value, but used reasoning as a filter to determine whether, where, and how a new piece of information would fit in his planned solution. Tom also referred to the task requirements, but his main focus was on the problem-solving task itself and whether his solution was aligned with the task. Ultimately, Tom's reasoning drove his solution process by identifying and bridging gaps among the problem-solving task, current solution, prior knowledge, and new information.

5. Conclusions and implications

Using the PR-SG model (Ge et al., 2016) as a cognitive framework for ill-structured problem solving, the current study sought to understand the iterative nature of IPS and the driving factors behind the iterations. The three representative cases provided an illustration of qualitatively unique IPS approaches and processes, and identified four key factors behind the iterations.

The current study is significant in several aspects. First, the study complemented existing IPS models (Brand-Gruwel et al., 2005) by providing a concrete account of iterations in the IPS process. Specifically, by examining evolving PR-SG's as "snapshots" of dynamic, self-regulative IPS processes, the study afforded an in-depth understanding on how students embarked on and defined an IPS task, and how their task definitions evolved towards a final solution. Second, the study revealed four key factors in IPS: prior knowledge, searched information, reasoning, and task requirements. Previous studies have examined some of the factors separately. For example, Hill and Hannafin (1997) identified prior knowledge as a key factor in IPS; prior knowledge was also found to contribute to ill-structured problem solving (Hmelo-Silver et al., 2007; Tawfik et al., 2018). The findings from this study suggested that prior knowledge could be used differently to either contribute to or interfere with successful IPS. Third, and more importantly, the study demonstrated how the four identified factors could act as triggers to drive different iteration patterns among the three divergent cases. Past studies have examined some of the factors. For example, Land and Greene (2000) investigated two factors that are similar to the information-driven and reasoning-driven approaches in this study, and found that the reasoning-driven approach was critical to developing coherent solutions. This study simultaneously examined four driving factors, which presented a comprehensive landscape of IPS. Fourth, methodologically, the study took on a qualitative approach to holistically examine individual IPS cases, which complemented existing quantitative analyses of think-aloud or log data of different performance groups (Brand-Gruwel et al., 2005; Zhou, 2013).

Although experts may largely rely on their prior knowledge to accomplish an IPS task, in the educational context where learners are often not content experts, IPS tasks are designed with the goal for learning. That is, it is expected that learners gain new knowledge and skills from working on an IPS task. The current study offers a few implications for teaching and facilitating IPS in a learning context. Critically, educators need to pay attention to how the four factors influence learners' IPS processes. Scaffolds should be in place to promote a positive and productive impact of prior knowledge, searched information, reasoning, and task requirements. For example, students should be guided to not only connect an IPS task to their prior knowledge, but also to use their prior knowledge as the departure point *to seek more information for verification or*

elaboration, which serves to solve the problem at hand. Students should also be prompted to continuously assess and reflect on their current understanding of the task, how it progressed from earlier understandings, and whether a gap exists between the current solution and the searched information, IPS task requirements, and their existing knowledge. Educators should also guide students to reason where and how to meaningfully integrate searched information into their existing solution.

The findings of this study are limited by the small sample size. While four key factors (prior knowledge, searched information, reasoning, and task requirements) surfaced from the data in this study, learners' individual differences such as cognitive skills, self-confidence, and motivational beliefs were likely behind learners' differential focus in IPS. For example, reliance on prior knowledge or searched information might be manifestations of learners' personal beliefs and cognitive skills (Hofer & Pintrich, 1997). Future research should investigate a larger pool of learners, and take under investigation participants' age, prior knowledge, educational levels, and other cognitive and motivational characteristics. Further, future studies should examine IPS in naturalistic settings such as completing IPS tasks for a course, since it is possible that participants show different problem-solving approaches between a coursework setting and the experimental setting. Lastly, instructional strategies should be designed and investigated to help students productively manage their prior knowledge, searched information, reasoning, and task requirements for effective IPS.

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Appendix I

IPS task description provided to students

Your Task

You work for a consumer's magazine, and are responsible for a column that answers readers' questions. Recently you have received quite a few inquiries. Essentially, they ask the same questions, "How to deal with food that is expired? Can we continue to eat them?" Your supervisor trusts you to do a research on the Internet, and use the information you find to write a response to these questions. You will use Microsoft Word to write a one-page response. Keep in mind that you need to use the information from the Internet to build your argument.