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Jean-François Rouet<sup>a</sup>, Zsofia Vörös<sup>a b</sup> & Csaba Pléh<sup>b</sup>

<sup>a</sup> CNRS and University of Poitiers, 5 rue Théodore Lefèbvre, Poitiers, F-86000 Poitiers, France

<sup>b</sup> Budapest University of Technology and Economics, Budapest, Hungary

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## Incidental learning of links during navigation: the role of visuo-spatial capacity

Jean-François Rouet<sup>a\*</sup>, Zsolia Vörös<sup>a,b</sup> and Csaba Pléh<sup>b</sup>

<sup>a</sup>CNRS and University of Poitiers, 5 rue Théodore Lefèbvre, Poitiers, F-86000 Poitiers, France; <sup>b</sup>Budapest University of Technology and Economics, Budapest, Hungary

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We investigated the impact of readers' visuo-spatial (VS) capacity on their incidental learning of page links during the exploration of simple hierarchical hypertextual documents. Forty-three university students were asked to explore a series of hypertexts for a limited period of time. Then the participants were asked to recall the layout and the contents of the pages. We found that low VS capacity readers had more difficulty recalling the links located at a deeper level in the page hierarchy. A content map included in half the trials had a limited effect on recall accuracy. We conclude that reading networked digital documents taps VS working memory, possibly due to readers' attempts to construct a topological representation of the network that coexists with the semantic representation of the contents.

**Keywords:** hierarchy; hypertext; incidental learning; navigation; visuo-spatial capacity

### 1. Introduction

Electronic publishing is having a profound impact on what, where and how people read. Digital technologies have revolutionised the art of designing and inter-connecting texts in the form of complex networks (Crane 2005). Within less than 20 years, millions of people all over the world have learned to access electronic texts through devices ranging from desktop computers to smart phones and digital pads. To the educated reader, Web browser tools such as scroll bars and hyperlinks are becoming as familiar as tables of contents, chapters and page numbering used to be.

At the same time, the online display of textual information has brought new challenges to readers, because of the very constraints of the electronic medium (Dillon 1994, van Oostendorp and de Mul 1996, Rouet 2006). Electronic display screens are usually smaller than printed pages (holding the respective grain size constant), thus increasing the need for scrolling, paging and link clicking. Early studies have evidenced some of the specific cognitive issues that users encounter when they engage in sustained, in-depth processing of extended textual documents. Among these issues are the well-known phenomena of disorientation and cognitive overload (Conklin 1987, Foss 1989). Despite tremendous improvements of the technology (i.e. larger screens with a sharper contrast and finer grain) and the emergence of a science of design for digital documents (Nielsen 1999, Mayer 2005), these issues have remained

constantly documented in the empirical literature of online reading and Web usability (Kim and Hirtle 1995, Ahujaa and Webster 2001, Gwizdka and Spence 2007, Juvina and van Oostendorp 2008, Amadiou *et al.* 2009, Madrid *et al.* 2009).

The processes that underlie readers' ability to mentally represent a nonlinear arrangement of textual information pages are still partly unknown. The evidence suggests that both individual and design factors are involved. Prior content area knowledge and reading ability obviously play a role in on-line reading just as they do in reading printed materials. Other cognitive abilities, however, may play a more specific role in electronic environments. This is the case, for instance, of people's ability to comprehend and remember spatial arrangements of objects or symbols, or 'visuo-spatial (VS)' ability. However, it is still unclear to what extent hypertext navigation requires the use of VS working memory, and whether low-capacity readers are at a disadvantage when encoding the global organisation of hypertext pages.

The purpose of this study was to assess the role of VS working memory when navigating a simple hypertext hierarchy, and thus to shed some more light on the mechanisms underlying orientation in nonlinear documents. We started with a brief review of the issue of hypertext navigation in relation to design and individual differences. Then we reported an experiment in which we tested the assumption that readers with

\*Corresponding author. Email: jean-francois.rouet@univ-poitiers.fr

a high VS span are more likely to encode page links at a deeper level in the hierarchy as they navigate a simple website with the purpose of learning the contents.

### 1.1. Navigation and orientation in hypertext

Ever since the emergence of the hypertext paradigm, spatial metaphors such as navigation and orientation have been widely used to describe the experience of reading networked text structures (Conklin 1987, Edwards and Hardman 1989, McDonald and Stevenson 1996). Navigation represents the actions taken by hypertext readers as they move from one page to another, and the resulting ‘itinerary’ of a reader in a hypertext network. Orientation denotes a sense of the overall organisation of the contents, e.g. where a certain page is located with respect to the overall linking structure of the hypertext.

Despite the use of these metaphors, the relevance of the analogy between semantic and real spaces is not totally straightforward. First, the semantic relations that underlie the linking of information page rarely correspond to actual spatial relationships (Dillon *et al.* 1993, Farris *et al.* 2002). Furthermore, hypertext navigation patterns vary greatly as a function of readers’ information needs or goals (for an extended discussion, see Kammerer and Gerjets, 2011). Finally, cognitive models of Web navigation (e.g. Pirolli and Card 1999, Juvina and van Oostendorp 2008) assume that users organise their itineraries in a stepwise fashion, by assessing the respective relevance of the available navigation options. These models put a strong emphasis on the information ‘scent,’ i.e. the respective relevance of the various links that appear on a given page, in determining the reader’s next move. They pay little consideration to the possible intervention of VS processes during hypertext navigation.

Nevertheless, readers’ ability to navigate digital documents seems related to their awareness of the organisation or ‘topology’ of the document space. For instance, hypertext readers use the home page as a landmark, especially when the global organisation of the system is not readily understandable (Britt *et al.* 1996). Interestingly, readers sometimes prefer to retrace their steps backwards through the sequence of pages they have traversed, as opposed to ‘jumping’ directly to the home page, which has been interpreted as their effort to maintain a sense of coherence or orientation (Mohageg 1992, Foltz 1996). Furthermore, as further detailed below, spatial metaphors embedded in hypertext systems generally facilitate information retrieval and learning.

Orientation in hypertext poses a specific problem in that the global organisation of the document is rarely available to the user. Most often, users can display

only a portion of a page at a time, and they need to scroll and click in order to move across pages. Each new piece of information displayed replaces the previous one, unless it opens in a new tab or window. But overlapping tabs or windows in turn create a problem to the user when it comes to going back to a previous piece of information (Foss 1989). A reasonable assumption, drawing on the analogy between information and physical landscapes, is that users encode landmarks as well as route and survey knowledge of the page structure as they visit and revisit the same pages. However, this assumption has yet to receive clear empirical support.

In summary, there is evidence that when reading through networks of information pages, readers experience phenomena similar to those involved in moving around and representing physical environments. This provides support for the general research assumption that spatial ability, and particularly the spatial component of working memory, may be involved in navigation and incidental learning of hypertexts.

### 1.2. Visuo-spatial working memory, navigation and learning in hypertext

Dimensions of individual differences such as prior knowledge, cognitive style or memory capacity play a role in readers’ ability to learn the structure of hypertexts (Chen and Rada 1996, Ford and Chen 2000, Graff 2005, Naumann *et al.* 2008). Because of the analogies between textual and physical spaces, research has focused on the possible role of so-called spatial abilities, which encompass one’s ability to represent and manipulate visual and spatial information. Early studies found relationships between spatial visualisation and readers’ ability to retrieve information in hypertext systems (Chen and Rada 1996, Chen and Czerwinski 1997, Nilsson and Mayer 2002, Downing *et al.* 2005). For instance, Nilsson and Mayer (2002) showed a positive relation between college students’ VS ability (as assessed by the Minnesota Paper Board Form test) and their search accuracy in an on-line encyclopaedia. Downing *et al.* (2005) found that students with better visualisation abilities (based on paper folding tests) were faster at retrieving relevant articles in an authentic bibliographic database.

Recent research has focused on the potential role of the VS sketchpad in working memory (Baddeley and Logie 1999). The rationale is that in order to construct a representation of the hypertext, readers have to devote attention to the respective position of pages as they go through them, which may tap working memory resources. Pazzaglia *et al.* (2008) found evidence that the verbal and VS components of

working memory affected learning from hypermedia at distinct levels. Whereas verbal memory predicted students' learning of the semantic contents, VS memory was related to students' learning of the structure of the document. Vörös *et al.* (2009) also found that low VS capacity users had more trouble remembering the structure, but not the contents of simple hierarchical hypertexts. A content map was more beneficial to these readers than to those with a higher capacity.

Disorientation and other navigation problems have often been related to the issue of depth in link hierarchies. Indeed, deeper hierarchies are harder to navigate (Larson and Czerwinski 1998) especially for older users and/or those who experience limitations in their VS abilities (Freudenthal 2001, Rouet *et al.* 2003). Deeper hierarchies may pose a special problem to low VS capacity users, as they increase the length of the path or 'route' to be remembered from the starting point to the target. Indeed, Freudenthal (2001, Experiment 2) found that participants' selection time at the deeper levels of a hierarchical menu system was significantly related to their spatial ability. It is likely, then, that readers with limited VS capacity would have more trouble building cognitive maps of the link structure when navigating hypertext documents.

### 1.3. The role of overviews and spatial metaphors

Due to the analogy between hypertext and physical spaces, spatial metaphors have been used from the onset to describe hypertext and hypertext-based activities (Kim and Hirtle 1995). Numerous experiments have demonstrated the value of inserting content maps in networked multi-page documents (e.g. Dee Lucas 1996, McDonald and Stevenson 1996; see also Kim and Hirtle 1995, Rouet and Potelle 2005, for reviews). Padovani and Lansdale (2003) found that a spatial metaphor facilitated information retrieval in a 29-page website with a hypertext structure. The spatial metaphor was that of a house where the pages were rooms and the links were passages across adjacent rooms. The non-spatial metaphor was that of a social network where nodes were students and links were connections across them. Each page contained a brief description of the contents. The task was to locate five specific targets (either people or flowers) and then later to return to each of them. Users were much more efficient with the spatial than with the non-spatial version of the site. Bromme and Stahl (2005) found that the type of metaphor suggested to hypertext users prior to their exploration of the system (i.e. a book or a space) influenced their navigation patterns. Nilsson and Mayer (2002) found that a content map facilitated retrieval from an online encyclopaedia. However, the

map also tended to lower users' level of engagement in learning the structure of the materials. Finally, Potelle and Rouet (2003) found that hierarchical, but not network, maps benefited novice readers' comprehension of a small hypertext. They concluded that the type of device used to facilitate orientation and learning had to be carefully tailored to the users' needs and prior knowledge. Indeed, spatial metaphors must be distinguished from pictorial representations of contents. Even though pictures were found to facilitate comprehension in many situations, they do not seem particularly relevant for signalling document contents. Experiments have found that website interfaces that rely on iconic representations of contents tend to hinder retrieval (Fajardo *et al.* 2006).

The effectiveness of content maps and other spatial metaphors adds support to the view that learning hypertexts and real environments may rely in part on similar, VS processes. Indeed, planning and executing routes in a hypertext network is in large part analogous to moving through a physical space. In both cases, routes may be based on one's knowledge of landmarks, one's knowledge of familiar itineraries or one's learned map of the environment (survey-type of knowledge). Hypertext navigation may be facilitated, to some extent, by providing the user with content maps.

### 1.4. Rationale

The main purpose of this experiment was to examine how readers with high vs. low VS memory span encode the linking structure of a hypertext as part of their navigation. In most website navigation activities, users focus on contents, either because they need to access a particular piece of information or because they need to learn about a particular topic. Therefore, the learning of the linking structure is most often incidental. Prior research suggests that hypertext readers encode the linking structure as they navigate, but only to the extent that they can devote attentional and working memory resources to this incidental task. Consequently, our main assumption was that readers with a lower VS working memory span would encode less information about the hypertext layout as they explore its contents.

Furthermore, in hierarchical hypertext networks, the likelihood that a link will be encoded as part of navigation decreases with its position in the hierarchy (Freudenthal 2001, Rouet *et al.* 2003). Top-level links are visited earlier in the process and more likely to be revisited later. Thus, they should have a higher probability to be encoded as landmarks. Lower-level links may be more difficult to encode, as users seem to keep track of their route from the home page till the current page. As a result, readers with a lower VS

memory span may have trouble encoding links deeper in the hierarchy. In other words, they would be less likely to retain links deeper in a hierarchical hypertext, compared to high-span users.

Finally, we predicted that the impact of VS capacity would decrease when a map representing the hypertext topology was included in the hypertext. We assumed that readers would have a chance to recode topological relations verbally and thus to recall them later based on verbal as much as VS cues.

## 2. Method

### 2.1. Participants

Participants were 43 students enrolled in various programs at a French public university (average age = 21 years; 11 males and 32 females). Thirty-four students participated for course credit, and the others participated voluntarily.

### 2.2. Materials and apparatus

A website was developed for the purpose of this and other similar experiments. The website gave access to several hypertexts and recorded users' navigation.

Sixteen distinct hypertexts were developed for the purpose of this experiment. They dealt with four different topics (fish, flowers, mammals and vegetables). Within each topic, the hypertext presented various species or types, each on a distinct page. Content pages were arranged according to a four-level hierarchical structure (Figure 1). The position of each page within the hierarchy was assigned randomly. Thus, the links across pages did not bear any particular meaning, except that they allowed the reader to

navigate from one species to another. All items had four levels of pages, but the specific arrangement of pages varied from one item to another.

Each page contained the name of the species, a sentence presenting some information about the species and a series of buttons corresponding to the linked pages (Figure 2). The page also contained a 'home' button that pointed to a home page with just the name of the topic and a link to the content page at the top of the hierarchy.

For each topic, four versions of the hypertext were created. The 'nine-page version' presented nine distinct species, whereas the '12-page version' presented 12 species, each on a different page. Furthermore, a content map was included in the 'map version', whereas the 'no map version' included only page links. The content map presented the hierarchical structure of the hypertext. It could be accessed from any content page through a 'MAP' button presented at the bottom right (Figure 2). Once the map was displayed, the participant could go to any content page by clicking on its label.

Thus, the four versions for each topic were the nine-page no map, nine-page with map, 12-page no map and 12-page with map. In addition to the 16 critical hypertexts, two additional items were designed for training purposes.

Two post-tests were designed to assess subjects' memory for the hypertext contents. In the content recognition test, the participant was given a list of six species names and a list of 15 content words, among which six had been actually presented on a page. The participant had to link each of the six species names to the correct content word. One score point was granted for each correct linking.

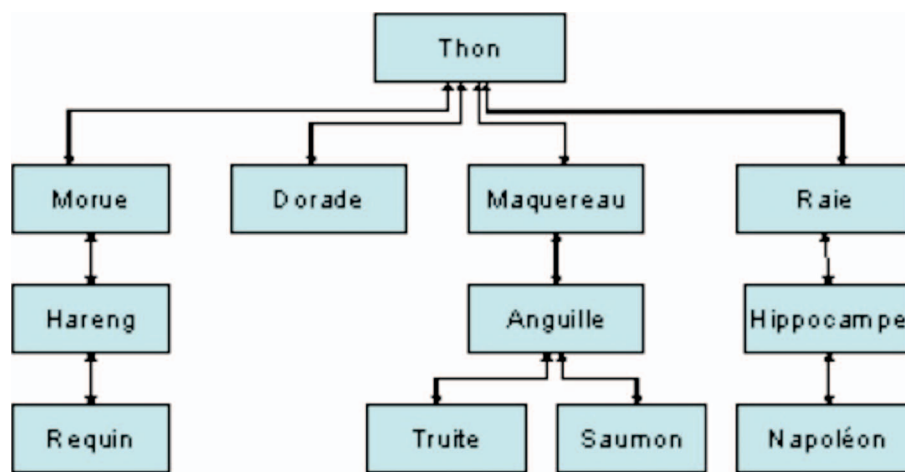


Figure 1. Example of a hierarchical hypertext used in the experiment. The Figure displays the content map that was inserted in the hypertext in the 'map' condition.

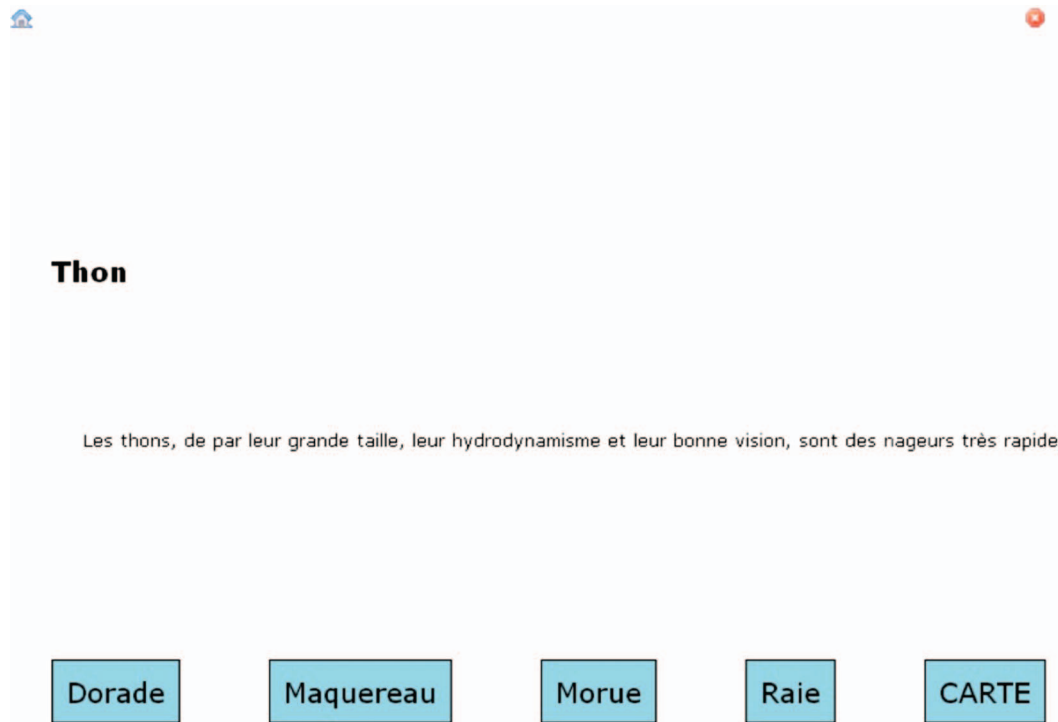


Figure 2. Example of a content page (Hypertext on 'Fish', page on 'Tuna'). The button at the lower right is linked to the content map ('CARTE').

In the layout recall test, the participant was given a list of the species names together with six distractors. The page also contained a large blank space. The participants were asked to draw a diagram showing the links between content pages. One score point was awarded for each pair of pages correctly linked.

The experiment also used the Corsi Block-like dynamic matrices task of Pickering *et al.* (2001), a widely used measure of the VS sketchpad working memory capacity. The test requires participants to learn a sequence of highlighted cells in a matrix and then to reproduce the exact same sequence. The sequence, flashing time of cells and time between flashings are controlled by the software. In our version of the test, the size of the sequence increased from three to nine cells. Participants went through five trials for each sequence size. They moved on to the next series as long as they completed at least two successful trials. One score point was awarded for each successful trial. Score points were weighted by the size of the series. For instance, a successful trial at the three-cell level earned three points. The maximum possible score was 210.

Finally, the experiment used three additional tasks aimed at controlling potential confounded factors of individual differences:

*Reading fluency:* The French-language reading test 'La pipe et le rat' (Lefavrais 1986) was used in the

experiment. The test requires participants to go through a list of 486 common words among which 243 are animal names. The words are presented on three pages for a total of 81 lines (i.e. six words per line). The participants have to locate and underline as many animal names as they can within a 3-minute period. The score is the total number of names correctly underlined minus the number of names mistakenly underlined.

*IT familiarity and frequency of use:* A three-item inventory asked participants to rate their familiarity with the use of computers, keyboard and mouse on a five-point scale. An additional eight-item inventory asked participants to report their frequency of engagement in a number of typical computer and Internet uses (e.g. information search and email) on a scale from 1 to 6. Familiarity and Engagement scores were obtained by summing up the participant's ratings across individual items. The resulting scales ranged from 3 to 15 for Familiarity (Cronbach's  $\alpha = 0.83$ ) and from 8 to 48 for Engagement (Cronbach's  $\alpha = 0.85$ ).

### 2.3. Procedure

The students participated individually in a single session of about 1 hour. They sat in front of a

standard PC with a 19" thin film transistor (TFT) screen, in a small experiment room. The distance between the computer screen and the participant's face was about 60 cm. The participant was given the questionnaire asking for their familiarity with computers, Internet use and demographic information.

In the critical task of the experiment, the participants had to explore a hypertext for a maximum of 3 minutes in order to learn its contents. The 3-minute limit was set to control for any individual differences in the management of study time. A pilot study showed that the time period was sufficient for participants to open and read all the contents at least once (remember that each page only contained a title, one sentence and a list of links). The participants were informed that they would be tested for their memory of the contents, but no specific information about the demands of the test was given in advance.

The participants went through one practice item and two critical items in the map and the no-map conditions. The order of presentation of the conditions was counterbalanced across subjects.

First, the participant was introduced with the hypertext presentation system using a practice item. The experimenter demonstrated and explained how to move across pages. Then, the participant could explore the practice item for 3 minutes. At the end of the navigation period, the participant was asked to exit and was given the content recognition and the layout memory tasks.

After completing the practice trial, the participant took two critical trials in the same condition. One trial involved a nine-page item and the other involved a 12-page item. For each trial the order of the tasks was the same: a 3-minute exploration period, followed by the content recognition and the layout memory tests.

After the second critical trial had been completed, the participant was given the Corsi blocks test and the reading test. Then the practice item for the other presentation condition (map or no map) was introduced, followed by the two critical trials. The directions and order of tasks were the same as in the first condition.

The order of presentation conditions (map vs. no map) and the order and contents of the two critical items within each condition (9 vs. 12 pages) were counterbalanced across participants. Each participant saw one item in each of the four versions, and one item with each of the four contents. Contents, number of pages and map condition were counterbalanced across participants so that each content appeared in the four versions.

#### 2.4. Predictions

The main predictions concerned the effects of participants' VS span and the availability of a content map

on participants' navigation and memory for the hypertext layout. We did not anticipate any difference due to VS capacity as regards navigation patterns, since the 3-minute period of time was enough for visiting each page but left little opportunity for participants to engage in multiple re-readings of the pages. We conjectured, however, that participants would spend relatively more time on the map, when available, in the 12-page than in the nine-page condition. This is because the map would be more helpful in more complex items and also because the 12-page map contained more information than the nine-page map.

Furthermore, we predicted that participants with a lower VS span (or low-VS) would recall fewer links than participants with a high VS span (or high-VS). We also expected the no-map version to yield poorer results than the map version.

In addition, the difference between high- and low-VS groups should increase with the number of pages in the hypertext. Conversely, the difference between high- and low-VS groups should decrease when the site included a map of the layout. The reason is that participants would have a chance to recode the layout in the form of verbal propositions (e.g. 'the "tuna" page is below the "cod" page'), thus compensating for their relatively poorer VS skills.

Because content recognition depended mostly on verbal comprehension and memory, we did not expect any difference between low- and high-VS groups on this measure.

### 3. Results

Due to an undetected technical flaw, one of the pages of the 'mammals' hypertext could not be accessed in the 12-page, no map condition. Therefore, all the measures for this item were corrected to ignore the missing page. In the following statistical analyses, effect size is estimated using partial  $\eta^2$ .

#### 3.1. Control measures

Participants were separated into low VS (VS-) and high VS (VS+) subgroups as a function of their scores at the Corsi blocks test. Table 1 shows the average scores of the two subgroups on this and the other control measures performed as part of the experiment.

As can be seen on Table 1, the median split on the raw Corsi blocks test scores yielded two sharply contrasted groups ( $t(42) = 9.32, p < 0.001$ ). These two groups, however, did not differ in terms of reading fluency, familiarity with computers or frequency of Internet use (all  $p$ 's  $> 0.10$ ). Thus, variations of

performance across groups on the experimental tasks may not be attributed to confounded factors of reading fluency, familiarity with computer use or frequency of engagement in computer and Internet-related activities.

### 3.2. Navigation data

The average proportion of pages visited during the navigation phase ranged from 92% to 98% of the pages, depending on the condition. A three-way, mixed-design analysis of variance (ANOVA) with VS capacity as a between-subject factor and number of pages and map as within-subject factors showed neither significant main effect nor any interaction among the factors on the proportion of pages visited. Thus, the exploration of the contents was rather exhaustive, even though some participants occasionally failed to open some pages. Most important, the no map condition did not decrease navigation

completeness, probably because the hypertexts were rather small and hierarchically organised.

### 3.3. Layout recall

Scoring guidelines were designed in order to score the participants' drawing of the hypertext layout (see an example in Figure 3). The guidelines listed scoring rules regarding ambiguous drawings, e.g. links that did not explicitly connect two nodes or links that were split into multiple sublinks (the scoring template is available upon request to the first author). Two scorers rated a sample of the protocols with more than 90% agreement at the individual link scoring level. Discrepancies were resolved through discussion and addition of extra rules to the template. One of the scorers rated the rest of the protocols.

A global layout recall score was computed, summing up the number of correct links and discounting incorrect links to control for guessing and the total

Table 1. Average scores and standard deviations on the pre-tests and control measures.

|                          | Corsi blocks, <sup>a</sup><br><i>m</i> (SD) | Reading fluency, <sup>b</sup><br><i>m</i> (SD) | Familiarity with<br>computers, <sup>c</sup> <i>m</i> (SD) | Frequency of<br>Internet use, <sup>d</sup> <i>m</i> (SD) |
|--------------------------|---|--|---|--|
| Low VS ( <i>n</i> = 22)  | 36.36 (10.10)                               | 108.10 (17.50)                                 | 11.64 (1.89)  | 16.82 (6.44)   |
| High VS ( <i>n</i> = 21) | 75.29 (16.40)                               | 111.50 (20.40)                                 | 12.14 (2.31)  | 17.05 (9.12)   |

Notes: <sup>a</sup>Scores are the number of correct trials, weighted by the difficulty level of the trial (max = 210); <sup>b</sup>Score is the number of words correctly underlined, minus the number of words mistakenly underlined (max = 243); <sup>c</sup>Score is the sum of IT familiarity scores reported by the participant (max = 15); <sup>d</sup>Score is the sum of the frequencies of IT uses reported by the participant (max = 48).

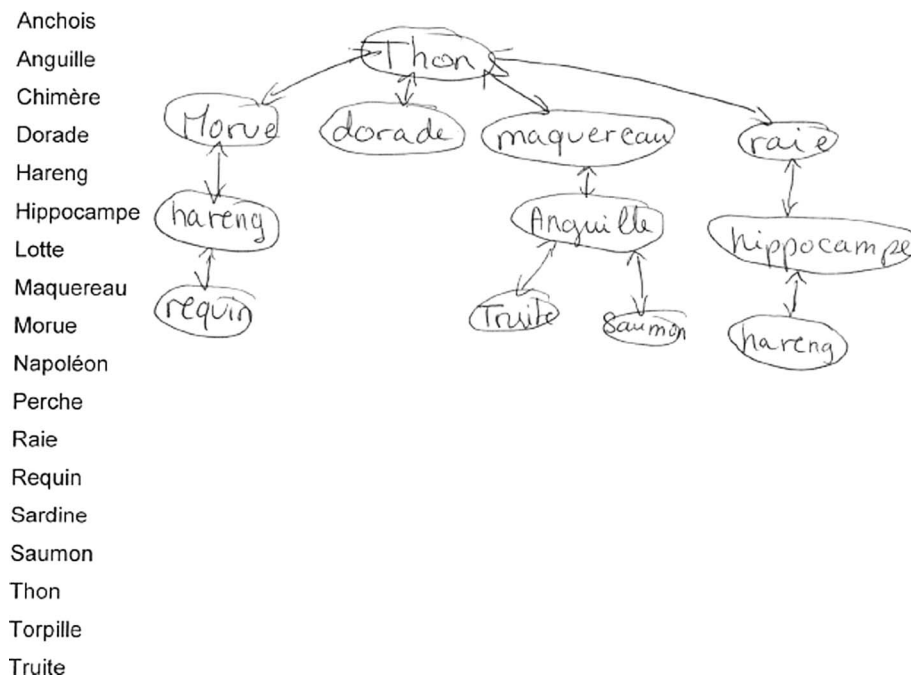


Figure 3. Sample participant's response to the layout recall task.



number of links. Based on similar measures published in the literature (e.g. Padovani and Lansdale 2003, Vörös *et al.* 2009), we used the following formula:

$$\text{Layout recall} = (\text{correct links}/\text{total links drawn} + \text{correct links}/\text{total possible links})/2$$

The layout recall score ranged from 0 (very poor score) to 1 (perfect score). Table 2 shows the average layout recall score as a function of VS span, number of pages and the presence of a map.

A three-way ANOVA with VS capacity as a between-subject factor and number of pages and map as within-subject factors found a significant effect of span ( $F(1,41)=8.45$ ,  $p < 0.01$ ,  $\eta^2=0.17$ ) on layout recall. Layout recall was also higher for nine-page than for 12-page items ( $F(1,41)=25.23$ ,  $p < 0.01$ ,  $\eta^2=0.38$ ). Even though the trend was in the expected direction, there was no significant effect of the map on layout recall and no significant interaction ( $p > 0.10$ ).

We further examined the layout recall data taking into account the position of links in the hierarchy. Because the pages were always arranged in four

hierarchical levels (see Figure 1), we were able to distinguish three levels of links independent from the total number of pages and the presence of a map. We computed the number of links correctly recalled at each level as a percentage of the total number of links experienced.

As shown in Figure 4, the inclusion of the depth parameter revealed the expected interaction between VS capacity and link level. A four-way ANOVA with VS capacity as a between-subject factor and number of pages, map and link depth as within-subject factors showed a main effect of link depth ( $F(2, 82)=41.02$ ,  $p < 0.01$ ,  $\eta^2=0.50$ ). The deeper the link in the hierarchy, the less likely it was to be included in the layout recall drawing. The percentage of links recalled was 85%, 71% and 57% for Level 1, 2 and 3 links, respectively.

Consistent with the global layout memory analysis, high-VS participants outperformed low-VS participants ( $F(1,41)=10.02$ ,  $p < 0.01$ ,  $\eta^2=0.20$ ), and recall was more complete for nine-page items than for 12-page items ( $F(1,41)=27.95$ ,  $p < 0.01$ ,  $\eta^2=0.41$ ). Again, however, the map did not significantly improve the recall of links ( $F(1,41)=1.17$ , NS).

As we had anticipated, there was a significant interaction between VS capacity and link depth ( $F(2,82)=6.73$ ,  $p < 0.01$ ,  $\eta^2=0.14$ ). The effect of link depth was stronger for low-VS participants. The percentage of Level 1 links recalled was 88% and 83% for high- and low-VS participants, respectively ( $F(1,41)=1.49$ , NS). In contrast, the percentage of Level 3 links recalled was 71% for high-VS participants but a mere 44% for low-VS participants ( $F(1,41)=15.07$ ,  $p < 0.01$ ). The effect of VS capacity on the recall of Level 2 links was also significant ( $F(1,41)=4.36$ ,  $p < 0.05$ ).

Table 2. Layout recall performance as a function of number of pages, inclusion of map and visuo-spatial span (VS).

|         | Nine pages  |             | Twelve pages |             |
|---------|-------------|-------------|--------------|-------------|
|         | With map    | No map      | With map     | No map      |
| Low VS  | 0.74 (0.32) | 0.75 (0.29) | 0.66 (0.25)  | 0.56 (0.21) |
| High VS | 0.91 (0.16) | 0.91 (0.11) | 0.72 (0.23)  | 0.70 (0.29) |

Note: Scores are expressed as a proportion of the total number of links included in the hypertext. Standard deviations are in parentheses.

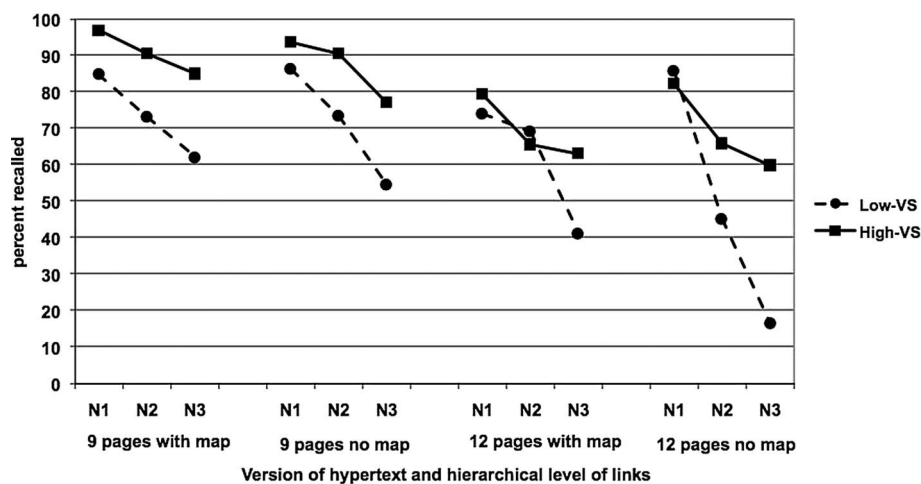


Figure 4. Percentage of links recalled as a function of hierarchical position and participants' visuo-spatial span (VS).

Thus, we demonstrated that limited VS capacity affected readers' ability to encode the link structure at deeper levels of the hierarchy. However, contrary to our expectations, the inclusion of a map did not specifically compensate low-VS readers' difficulties. There was no other significant interaction.

### 3.4. Content recognition

The percentage of content words correctly assigned to their respective page title was computed for each participant and each item. A three-way ANOVA with VS capacity as a between-subject factor and number of pages and map as within-subject factors showed that recognition was less accurate for 12-page than for nine-page items ( $F(1,41) = 5.18, p < 0.05$ ). There was no other main effect or interaction.

## 4. Discussion

The main goal of this experiment was to find out whether VS working memory is involved in the incidental learning of the arrangement of pages within hypertextual documents. Consistent with prior studies of spatial ability and electronic information use (e.g. Nilsson and Mayer 2002) as well as more recent studies of VS working memory and hypertext learning (Pazzaglia *et al.* 2008, Vörös *et al.* 2009), we found a positive relationship between readers' VS capacity and their incidental encoding of the hypertext structure during navigation. More specifically, our data suggest that low-capacity readers tended to lose track of the link structure as they navigated deeper in the link hierarchy. In contrast, high and low VS capacity participants did not differ in their recognition of content information. This is further evidence of the intervention of topological processes in the learning of non-linear multi-page documents. In the present study, the impact of VS capacity was not confounded with reading fluency or familiarity with computers or the Internet, as these variables were controlled.

Unexpectedly, the inclusion of a content map had a very limited impact on participants' learning of the link structure. One reason may be that navigation took place in a limited time, which precluded any rehearsal strategy using the map. There was no difference between high- and low-VS capacity participants' use of the map during navigation. Even though we failed to observe a significant impact of content maps on the incidental learning of the structure, one should not conclude that these devices are useless. Indeed, content representations are an important aspect of usability (Fajardo *et al.* 2006), and several studies have found positive effects of content maps (see Kim and Hirtle 1995, Rouet and Potelle 2005), especially for users with

low VS capacity (Vörös *et al.* 2009). The specific task conditions implemented in this experiment may explain our failure to replicate these effects. Because of the limited time and number of pages to be learned (nine or 12, as opposed to six or nine in the study by Vörös *et al.* 2009), the participants may have been prevented from learning from the map. Nevertheless, we replicated the effect of depth on memory for links, showing for the first time (to our knowledge) that readers with a low VS sketchpad capacity have trouble encoding the deeper links in a hierarchy of hypertext pages.

The finding that hypertext and spatial learning rely, in part, on similar memory processes has consequences at theoretical and empirical levels. At a theoretical level, theories of reading comprehension have focused on the issue of how readers represent the semantic contents of the text (Kintsch 1998). It has been assumed that information regarding the surface form of the text (e.g. the exact wording of the passage) was rapidly 'subsumed' under a deep, meaning-based semantic representation. This assumption may be challenged in the case of multi-page texts, especially when they are presented on-line. Understanding the topological organisation of pages then becomes an integral part of the comprehension experience. A topological representation is useful when making navigation decisions and also, perhaps, when returning to a previously visited page for later use. Thus, hypertext readers may spontaneously attempt to construct a representation of their itinerary as they explore a network of pages, which, in the end, results in a topological representation of the network that co-exists with the semantic representation of the contents. Our experiment suggests that building the topological representation taps the VS component of working memory (see also Pazzaglia *et al.* 2008, Vörös *et al.* 2009).

From a more practical perspective, the finding that navigating hypertext is analogous to learning a physical space adds to the need for designers to support orientation processes in non-linear information repositories. Shallow hierarchies with a clear signalling of the linking structure should facilitate low-VS readers' navigation, information retrieval and learning. This is especially important given the increasing use of on-line information among older adults (Pew Internet and American Life Project 2010) and the fact that VS capacity is generally found to decrease with age (Freudenthal 2001).

Some features of the experiment, however, limit the generality of the findings. First, we used materials with a small number of pages containing a very small amount of information. The balance between semantic and spatial processes may likely to change for websites

containing a larger number of pages and/or pages with more textual or pictorial contents. Second, the procedure involved a 3-minute exploration phase with no specific purpose or objective. As mentioned in the introduction, navigation has been found to be strongly context dependent, and other task contexts may lead to different findings (see Kammerer and Gerjets, 2011). Third, we only tested the short-term recall of links. In the longer term, the performance of high- and low-VS span participants might become more similar to each other.

Future research should seek to extend these findings by using more realistic materials and tasks. It would also be helpful to investigate potential cues that may specifically support the navigation of users with limited VS capacity.

In conclusion, the present study supports the view that hypertext navigation involves VS processes and that individual differences in VS working memory span may explain, in part, users' ability to make use of this specific way of accessing and perusing digital information.

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