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# How children navigate a multiperspective hypermedia environment: The role of spatial working memory capacity

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The use of hypermedia environments is increasing in school education. The interactivity in hypermedia environments challenges learners to autonomously navigate such environments. Particularly in multiperspective hypermedia environments (MHEs), which emphasize the multiperspectivity of a topic, it is important to apply navigational behaviors that take advantage of this information structure through which different perspectives can be selected and compared. However, we argue that and test whether the availability of sufficient spatial working memory (WM) resources is an important precondition for effectively engaging in this type of perspective processing. Specifically, we examined $N = 97$ German fourth-graders' navigational behaviors (i.e., perspective processing, content processing, and irrelevant processing) during hypermedia learning and their relation to spatial WM and performance. To this end, we developed an MHE on the biodiversity of 24 fish species. Participants' navigational behavior was determined via log file analyses, while their performance was assessed by exploration questions and inferential questions (about fish) and by scientific transfer questions (about the biodiversity of another species). Our results indicated that spatial WM was positively related to perspective processing, which was positively related to performance. Mediation analyses revealed that perspective processing partially explained the relation between spatial WM and performance. Thus, both spatial WM and perspective processing are important for benefitting from MHEs.



## 1. Introduction

Digital learning technologies such as instructional hypermedia environments enable innovative and interactive learning approaches to be used (e.g., Falloon, 2013). Instructional hypermedia environments, for instance, display multimedia materials (e.g., text, pictures, videos) in a nonlinear structure (e.g., hierarchical or networked). Particularly networked hypermedia structures are supposed to be appropriate for emphasizing the complexity of multifaceted knowledge domains that present the same content materials in a variety of different contexts (Jacobson & Spiro, 1995; Spiro & Jehng, 1990). As this type of hypermedia environment requires learners to simultaneously consider multiple viewpoints, it can also be referred to as a multiperspective hypermedia environment (MHE; see Lima, Koehler, & Spiro, 2002). Compared with traditional learning materials (e.g., textbooks) that have a linearly structured sequence, (multiperspective) hypermedia environments allow learners to autonomously navigate learning materials in a nonlinear fashion. More specifically, learners can decide what information to explore next and how to process this information (e.g., as text or videos). Although several studies have already examined which navigational behaviors might be effective for hypermedia learning in general (e.g., Lawless & Kulikowich, 1996), effective navigational behaviors in hypermedia environments that particularly emphasize the multiperspectivity of a knowledge domain (i.e., MHE) have received less attention. Moreover, we argue that effective navigation in MHEs requires a large amount of working

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memory (WM) resources (e.g., Baddeley, 2012), specifically spatial WM resources, such that not all learners are able to apply navigational behaviors that maximize their learning. To the best of our knowledge, this issue has not yet been empirically tested.

The present study focused on the relations between spatial WM capacity, navigational behaviors, and performance in the context of multiperspective hypermedia learning. More precisely, we investigated which specific navigational behaviors are beneficial for learning when dealing with an MHE. Moreover, we examined the association of spatial WM capacity with navigational behaviors and performance in MHEs. We investigated these research issues in a sample of school children, specifically fourth-graders, because innovative instructional environments (e.g., MHEs) are currently commonly advocated in the educational context (e.g., Falloon, 2013). Given the increasing interest in tablet computers, which seem to be more intuitive for younger children to handle than traditional computers (Lane & Ziviani, 2010), an application of such environments can also be found among elementary school children in particular. Surprisingly, to the best of our knowledge, studies on hypermedia learning are relatively scarce among this population. In particular the fourth grade is considered to be the inflexion point in which text comprehension, such as information extraction and understanding causal relations, which is important for successful hypermedia navigation, improves (Kaplan, 2013). Nevertheless, whether fourth-graders are indeed capable of successfully navigating an MHE remains to be clarified. Thus, it is particularly interesting to focus on how these environments can be used by this population.

### 1.1. Hypermedia learning

Hypermedia environments are information systems containing multiple information nodes that are interconnected in a nonlinear fashion. Moreover, the information is displayed in different representational formats such as text, pictures, or videos (Scheiter & Gerjets, 2007). Navigating the nonlinear structure of hypermedia environments involves a high degree of learner control because not only can learners choose what information to access, but they can also decide the order and the format they prefer to process it in (e.g., as text or video; cf. Gerjets, Scheiter, Opfermann, Hesse, & Eysink, 2009). Generally, one can differentiate between two types of hypermedia structures: hierarchical and networked (DeStefano & LeFevre, 2007). In hierarchical hypermedia environments, the interconnections between information nodes can be described as a tree structure with broader topics at higher levels and subordinate topics at lower levels. Networked hypermedia environments, by contrast, have a nonsequential structure that is characterized by associative links relating semantically similar information in the environment. According to the framework of cognitive flexibility theory (Jacobson & Spiro, 1995; Spiro & Jehng, 1990), networked hypermedia environments are ideal for displaying multifaceted knowledge domains that present the same content materials in a variety of different contexts. If these networked hypermedia environments are designed in a way that allows learners to simultaneously consider multiple viewpoints, they can also be referred to as multiperspective hypermedia environments (MHEs; cf. Lima et al., 2002). As an example of an MHE, Jacobson and Spiro (1995) asked learners to consider the impact of technology on 20$^{th}$-century society and culture from multiple perspectives such as progress-problems, freedom-control, or technological efficiency. The content materials were displayed in a multiperspective hypermedia structure, thus making it easier for learners to consider them from different conceptual perspectives.

The autonomous “criss-crossing of the conceptual landscape” (see Niederhauser, Reynolds, Salmen, & Skolmoski, 2000, p. 238) in MHEs is assumed to support constructive information processing so that a deeper elaboration of the learning material and a better comprehension of multifaceted topics can take place. Moreover, learners are supposed to develop more flexible cognitive structures that enable them to transfer acquired knowledge elements to novel problem contexts (Jacobson & Spiro, 1995). To benefit from these advantages, it can be assumed that MHEs (as well as hypermedia environments in general) require learners to engage in effective navigational behaviors. However, not all navigational decisions support comprehension and learning (e.g., Lawless & Kulikowich, 1996). The next section reviews differences in navigational behaviors concerning their effectiveness for exploring hypermedia environments.

### 1.2. Navigation in hypermedia environments

In the last two decades, various studies with both children and adults have investigated the effectiveness of navigational behaviors when learners explore (hierarchical or networked) hypermedia environments (e.g., Lawless, Brown, Mills, & Mayall, 2003; Naumann, Richter, Christmann, & Groeben, 2008; Richter, Naumann, Brunner, & Christmann, 2005; Puntambekar & Goldstein, 2007; Salmerón & García, 2011; Salmerón, Baccino, Cañas, Madrid, & Fajardo, 2009). Richter et al. (2005), for instance, demonstrated that more linear sequencing and less backtracking behavior (clicking backwards) produced more systematic navigational behavior and fewer orientation problems and were in turn related to higher learning outcomes. Salmerón et al. (2009) and Salmerón and García (2011) presented learners with a graphical overview of a hierarchical hypertext structure and found that initial processing of the overview best benefitted comprehension of the hypertext. In addition, choosing a coherent navigational path (i.e., subsequently navigating through semantically related pages) and focusing on task-relevant pages were also associated with better comprehension and learning (Lawless et al., 2003; Lawless & Kulikowich, 1996, 1998; Naumann et al., 2008; Puntambekar & Goldstein, 2007; Salmerón & García, 2011). By contrast, learners who spent more time interacting with the special features of the hypermedia environment (e.g., movies, animations, graphics) or whose navigational path revealed no logical order showed lower comprehension and learning performance (Barab, Bowdish, Young, & Owen, 1996; Lawless & Kulikowich, 1996; Lawless, Mills, & Brown, 2002).

Thus, navigational behaviors such as focusing on task-relevant pages and choosing a coherent or linear navigational path seem to be most effective for learning in (hierarchical and networked) hypermedia environments. However, in networked hypermedia environments that particularly emphasize the multiperspectivity of a knowledge domain, namely in MHEs (cf. Lima et al., 2002), it might not be sufficient to review task-relevant content in one systematic sequence because MHEs are not primarily designed to convey isolated factual knowledge in a specific order. Rather, they aim to convey broad conceptual knowledge about a topic, that is, an overview and understanding about how different information elements are related to each other from different conceptual perspectives (e.g., Jacobson & Spiro, 1995). For this reason, usually two types of navigational choices can be distinguished in MHEs; namely, the processing of perspectives and the processing of isolated content. More precisely, on the one hand, the processing of perspectives implies the selection of conceptual overview pages that allow the comparison of different information elements within a certain perspective (perspective processing). On the other hand, the processing of content implies the selection of a specific content page (e.g., a text or video) without taking the context (i.e., the constellations shown on the overview pages, which allow the comparison of different information elements within a certain perspective) into account (content processing). In the context of MHEs, perspective processing should arguably be more effective than content processing for acquiring conceptual knowledge as learners who process the different perspectives learn how different information elements are related. Moreover, these learners can also capture specific information about several content units at the same time. Learners who separately process content elements (content processing), by contrast, only learn isolated information about one single content element at a time. Furthermore, these learners do not get an impression about how this content element is related to other content elements. Thus, content processing should be less effective than perspective processing. Still, content processing is not considered to be ineffective as it should not hamper learning. It is only considered to be not particularly effective as this navigational behavior does not tap the full potential of an MHE (i.e., acquiring conceptual overview knowledge).

Beyond the navigational behaviors of perspective processing and content processing that are defined as task-relevant navigational behaviors (i.e., navigational behaviors addressing a given learning task), irrelevant navigational processing is also likely to occur in nonlinear settings. Irrelevant processing (i.e., navigational behaviors that do not address a given learning task) can result from distraction or disorientation in these learning environments (e.g., Scheiter & Gerjets, 2007). In line with previous research (e.g., Lawless & Kulikowich, 1996), irrelevant processing is likely to be ineffective in the context of MHEs for comprehension and learning. To the best of our knowledge, the effectiveness of these three different navigational behaviors (i.e., perspective processing, content processing, irrelevant processing) in MHEs has not yet been explicitly investigated, especially not with regard to elementary school children in general and fourth-graders in particular. Therefore, a central goal of the present study was to address this issue in a sample of fourth-graders using an MHE.

### *1.3. The role of spatial working memory capacity in hypermedia navigation*

Although the selection of conceptual overview pages to compare and relate various contents from different perspectives (perspective processing) is assumed to be effective, it also demands a great deal of cognitive and metacognitive resources (cf. Niederhauser et al., 2000; Scheiter & Gerjets, 2007). Consequently, not all learners will be able to engage in effective perspective processing. As we argue in the following, one learner characteristic that might be positively related to the effective use of this navigational behavior is (spatial) working memory capacity.

Working memory (WM) is a subsystem of human memory that primarily consists of two simultaneous functions: the temporary storage of information and the executive control of information processing (Baddeley, 2012). The storage of information is assumed to take place in different slave systems, either in the visual cache for visuo-spatial information or in the phonological store for verbal information (e.g., Baddeley & Logie, 1999). Concurrent information processing, by contrast, can be ascribed to the executive control, which can be decomposed into various executive processes such as focusing attention while inhibiting irrelevant information, updating of information, dividing attention between two important stimuli, making decisions, or switching between tasks (Baddeley, 2012; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000).

WM has been shown to be positively associated with a variety of learning outcomes such as school achievement in general or reading comprehension in particular (e.g., Alloway & Alloway, 2010; Seigneuric & Ehrlich, 2005). The impact of WM capacity has also been theoretically discussed in the context of hypermedia learning (Lowrey & Kim, 2009; Niederhauser et al., 2000) and has been empirically demonstrated (Lee & Tedder, 2003; Pazzaglia, Toso, & Cacciamani, 2008). For instance, Pazzaglia et al. (2008) could show in a sample of sixth-graders that students' WM capacity predicted their learning outcomes in a hierarchical hypermedia environment. However, the association of WM capacity and navigational processing in hypermedia environments has received less attention. There are only a few studies (Gwizdka, 2009; Juvina & van Oostendorp, 2008; Naumann et al., 2008) that investigated the influence of WM capacity on navigational processing, showing only limited evidence for such a relationship. In this regard, for instance, Naumann et al. (2008) found that undergraduate students with higher WM capacity benefitted more from a cognitive or metacognitive strategy training in terms of their learning outcome in a hypermedia environment than students with lower WM capacity and that this effect was partially mediated by students' task-related navigational behaviors (i.e., navigational behaviors that address a given learning task). However, for students who had not received any strategy training, the authors did not find any relationships between WM, task-related navigational behaviors, and learning outcome. Furthermore, Gwizdka (2009) and Juvina and van Oostendorp (2008) did not find WM capacity to have an impact on navigational behavior in samples of university students. It has to be noted, however, that all three studies applied working memory measures (i.e., operation span or reading span) that rather addressed the verbal or numerical component of WM (i.e., rather the phonological store) than the spatial component of WM (i.e., the visual cache). As will be argued in the following the latter component, that is, the storing and manipulation of complex spatial patterns, may be more important for effective navigation than the storing and manipulation of verbal materials (see Juvina & van Oostendorp, 2008).

From a theoretical point of view, particularly spatial WM is likely to be involved in a variety of navigational processes such as representing different navigation paths, making decisions about link selection, or representing the structure of the digital environment mentally (cf. McDonald & Stevenson, 1996; Niederhauser et al., 2000; Pazzaglia et al., 2008). In this vein, for instance, the study by Pazzaglia et al. (2008) demonstrated that spatial WM plays an important role in the ability to construct a representation of the hypertext structure. Moreover, especially navigational behaviors associated with perspective processing are likely to require spatial WM resources as learners need spatial abilities for switching between different conceptual perspectives as well as a good memory for the spatial structure of the environment in order to flexibly restructure their knowledge (Diamond, 2013; Niederhauser et al., 2000; Pazzaglia et al., 2008). Consequently, it seems likely to assume that only learners who possess sufficient spatial WM resources will be able to effectively apply perspective processing with regard to learning.

Moreover, during navigation learners are challenged to focus their attention and inhibit distracting information in order to avoid irrelevant processing. These processes are associated with WM resources, as high WM capacity helps to focus on relevant information and to avoid irrelevant information (e.g., Baddeley, 2002; McDonald & Stevenson, 1996). Therefore, it is reasonable to expect learners with high spatial WM resources to be able to avoid irrelevant processing, whereas learners with low spatial WM resources should show high levels of irrelevant processing. Finally, isolated content processing should not require spatial WM resources (since the characteristics of spatial WM resources such as, in particular, handling complex patterns seem not to be related to the processing of isolated content units).

Taken together, another goal of the present study was to investigate the relation of spatial WM capacity to navigational behaviors in an MHE, which has not been investigated yet. Specifically, we expected spatial WM capacity to be positively related to perspective processing and negatively related to irrelevant processing. By contrast, the navigational behavior of content processing was not expected to be significantly related to spatial WM capacity.

### 1.4. The present study

The present study focused on the relation between spatial WM capacity, navigational behaviors, and exploration performance and learning outcomes in a sample of fourth-graders dealing with an MHE. Specifically, we tested the following four hypotheses:

First, we wanted to replicate previous findings regarding the positive effect of (spatial) WM capacity on learning in hypermedia environments (e.g., Pazzaglia et al., 2008), thereby focusing on elementary school children, particularly on fourth-graders. Correspondingly, we predicted that spatial WM capacity would be positively related to children's exploration performance and learning outcomes when working in an MHE (Hypothesis 1).

Second, we tested whether spatial WM capacity would be associated with students' navigational behaviors. We hypothesized that spatial WM capacity would be positively related to perspective processing and negatively related to irrelevant processing. By contrast, we expected that spatial WM capacity would not be associated with content processing (Hypothesis 2).

Third, we addressed the extent to which the different navigational behaviors could be considered effective with regard to children's exploration performances and learning outcomes. Whereas we expected perspective processing to be positively and irrelevant processing to be negatively associated with children's performance, we expected that content processing would not be associated with performance in an MHE (Hypothesis 3).

Finally, we aimed to investigate whether the assumed positive association between spatial WM capacity and performance in an MHE could be explained by the use of effective navigational behaviors. Specifically, we hypothesized that the relation between spatial WM capacity and performance would be fully mediated by perspective processing (Hypothesis 4).

## 2. Method

### 2.1. Participants

The sample consisted of 97 elementary school children (40.2% female) at the end of Grade 4 from different elementary schools in Baden-Württemberg, Germany. As in Germany the school tracking system (low, intermediate, and high level schools) starts at Grade 5, the current sample still consisted of all ability levels. All children of the present sample were accustomed to use traditional computers in their school, however, not to use tablet computers, which we applied in the current study (see below). Nevertheless, 65% of the children indicated to be familiar with the use of tablet computers from home and 77% indicated to be experienced with touch screens in general. The children's age ranged from 9 to 12 ($M$ = 10.3, $SD$ = 0.45) years. Active parental approval for participation was obtained for all children.

### 2.2. Materials

#### 2.2.1. Learning domain and exploration tasks

We designed an MHE (based on the specifications of cognitive flexibility theory; Jacobson & Spiro, 1995; Spiro & Jehng, 1990) on the "biodiversity of fish" for the present study. The biological topic of "biodiversity" implies that a diversity of species is presented along a number of important conceptual perspectives such as their living environment or their eating habits (Lindemann-Matthies, 2005). Thus, it qualifies as an appropriate topic for MHEs. For the children, the fish topic was embedded in an aquarium setting that invited them to take on the role of a fish keeper. To adequately fulfill their role, they had to learn about 24 different fish species, for instance, about where they live or how they swim. To support the exploration of the fish environment, we provided the children with topic-exploration tasks that guided them through the learning phase. Importantly, these tasks aimed to convey a conceptual overview of knowledge about the topic by motivating the children to select different perspectives in order to find information (for further details on the exploration tasks, see 2.2.2 and 2.3.2).

#### 2.2.2. Multiperspective hypermedia environment (MHE)

We developed the MHE for a tablet computer because touch-screen interfaces are viewed as better adapted to the skills of younger children who find it more difficult to use a traditional computer (Lane & Ziviani, 2010). The first page of the MHE was an overview of 24 alphabetically ordered fish species represented with pictures (see Fig. 1).

Clicking on a specific fish picture enlarged the picture and produced two hyperlinks that allowed the children to engage in content processing by either reading additional text or watching a video about the fish. Furthermore, the alphabetical overview screen contained six colored hyperlinks that allowed access to six information pages representing the available perspectives according to which the fish could be explored (i.e., alphabetical overview, size, social behavior, living environment, swimming style, and eating habits). By clicking on one of these fish-perspective hyperlinks, the alphabetical order of the fish was reordered according to the categories corresponding to a particular perspective (see Table 1 for all categories).

For example, by clicking on the "living environment" hyperlink, all fish were sorted into one of the three categories "Mediterranean Sea," "River," or "Tropical coral reef" (see Fig. 2). Thus, clicking on the perspective-hyperlinks and comparing how the fish were subsequently reordered helped the children to engage in perspective processing and as a consequence made reading the isolated content pages unnecessary with regard to information about their living environment.

Finally, different hyperlinks provided filtering (e.g., fish without scales) and could be used to highlight a subgroup of fish, thus allowing the children to consider the fish from different angles to stimulate perspective processing. Each perspective page allowed access to all fish and to the hyperlinks for the different fish-perspectives and for filtering (see Fig. 3 for an exemplary extract of the structural associations between perspectives and contents in the MHE).

In the following, two example tasks will be described for illustrating the strategies of perspective processing and content processing when exploring the MHE about fish. One exploration task, for example, asked the children to figure out the living environment of the chub. To answer this question, the children had several options for exploration. On the one hand, they could use a perspective processing strategy by selecting the "living environment" perspective and then by detecting that the chub belonged to the "river" category (see Fig. 2). On the other hand, they could engage in a content processing strategy by clicking on the picture of the chub and could extract the relevant information either by reading the additional text or by watching the video about the chub (see Fig. 4).

Another exploration task challenged the children to compare two "plant-eater" fish, namely the nase fish and the surgeon fish. Again, to solve this task, on the one hand, children could select the different perspectives (e.g., living environment) and compare the

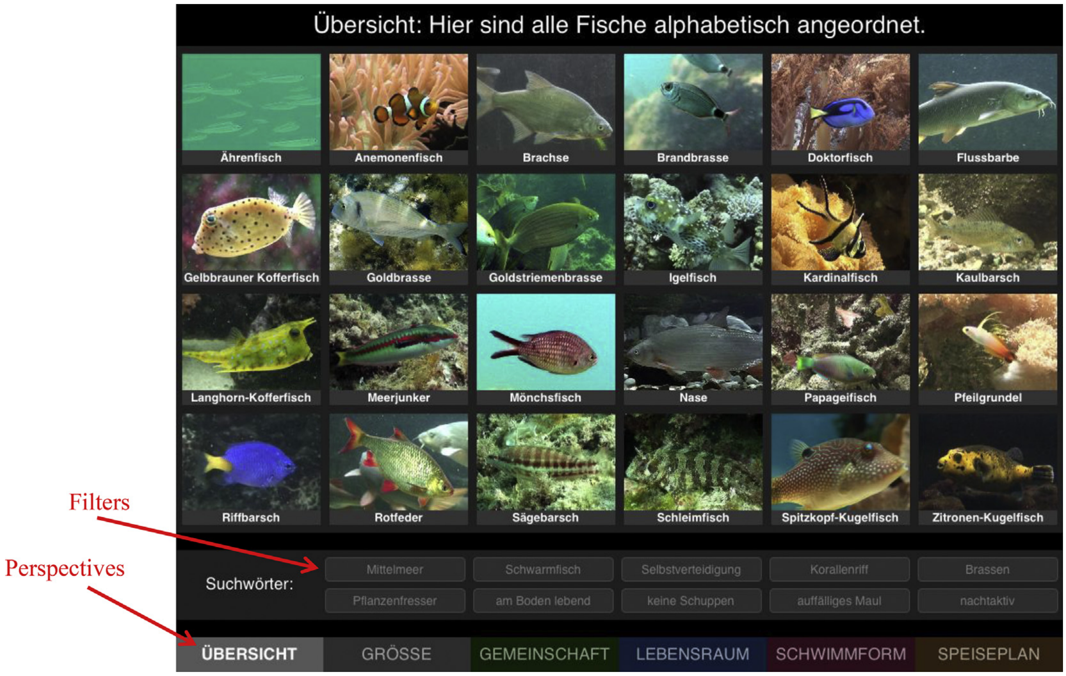


**Fig. 1.** Overview page of the MHE with all 24 fish ordered alphabetically, with hyperlinks for the six different fish-perspectives and for filtering.

**Table 1**
Overview of all six perspectives with the corresponding categories from the MHE.

| Perspectives | Categories | | |
|---|---|---|---|
| Alphabetical overview | – | – | – |
| Size | – | – | – |
| Social behavior | Swarm | Loner | Loose group |
| Living environment | Mediterranean Sea | River | Tropical coral reef |
| Swimming style | *Snaky-swimmer* (sub-carangiform) | *Breaststroker* (labriform) | *Finny-waver* (tetraodontiform) |
| Eating habits | Plant-eater | Plankton-eater | Shellfish-eater |

two fish according to their category classification (e.g., river vs. tropical coral reef; perspective processing). To facilitate and clarify the comparison, they could additionally use the filter “plant eaters” to highlight only this subgroup of fish (see Fig. 5). On the other hand, the children could thoroughly study both fish individually for a comparison by sequentially reading the specific texts about the two fish or by watching the corresponding videos (content processing).

Note that the instructional materials as well as the tasks were tested in a pilot study with several fourth-graders. Interviews with and observations of the children provided valuable hints about the suitability of the instructional materials and of the tasks with regard to comprehensibility, reading level, and working time. The final version of all materials was adapted accordingly so that all materials as well as all tasks could be considered as comprehensible, readable, and processable within the time prescribed for this age group.

### 2.3. Measures

#### 2.3.1. Navigational behaviors

With regard to students' navigational behaviors, as dependent measures we calculated the time (in s) each student spent with (a) perspective processing, (b) content processing, and (c) irrelevant processing. The tablet application recorded log files containing all actions taken by the students in the MHE. We analyzed these log files in order to classify students' navigational behaviors in terms of perspective processing, content processing, and irrelevant processing. As there is no predefined order of actions to occur in an MHE, students' navigational freedom results in a wide variety of potential action sequences. To classify these action sequences we did not use human coders but implemented deterministic pattern definitions and rule matching algorithms for each task based on abstracted descriptions of students’ actions and the resulting action sequences (about 1600 lines of JavaScript code).

In short, the first step was to classify students’ navigational behaviors automatically by defining rules that linked sequences of actions in the MHE unequivocally to the three classes of navigational behaviors (i.e., perspective, content, and irrelevant processing). In a second step, we matched these rules against the sequences found in the log files. If a match between a rule and a sequence from the log files was found, the navigational behavior could be classified as either perspective or content processing for the task. If no match was found for a sequence of the log files, it could be defined as irrelevant processing.

In particular, the procedure for our automatic analysis of the log files was as follows. The starting point of our analysis was the *raw representation of students' actions* in the log files. Second, by inferring additional context information we derived an *enriched representation of students' actions*. Third, based on these enriched representations of concrete actions we defined more abstract *action patterns* as well as *meaningful sequences of action patterns*. Finally, these sequences of action patterns were the basis for *classifying students’ navigational behaviors* as perspective processing, content

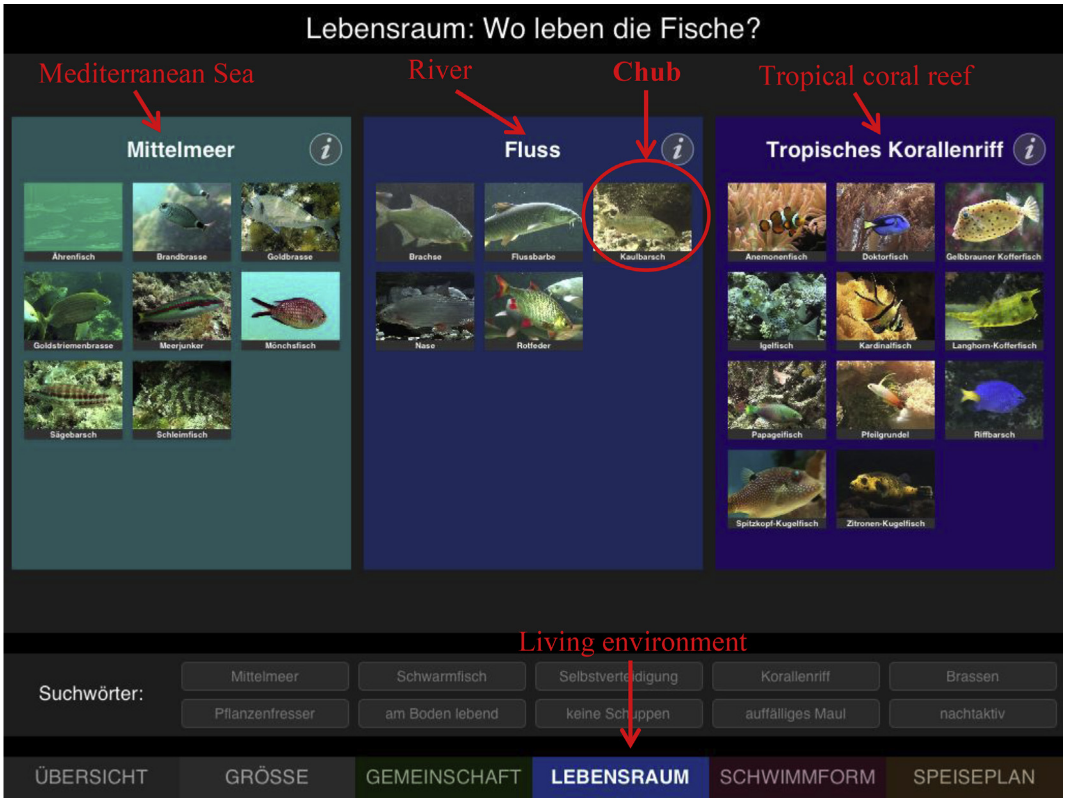


**Fig. 2.** "Living environment" perspective page ("Where do the fish live?") from the MHE with all fish sorted into the categories "Mediterranean Sea," "River," and "Tropical coral reef" (the chub is circled in red, see exploration task). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

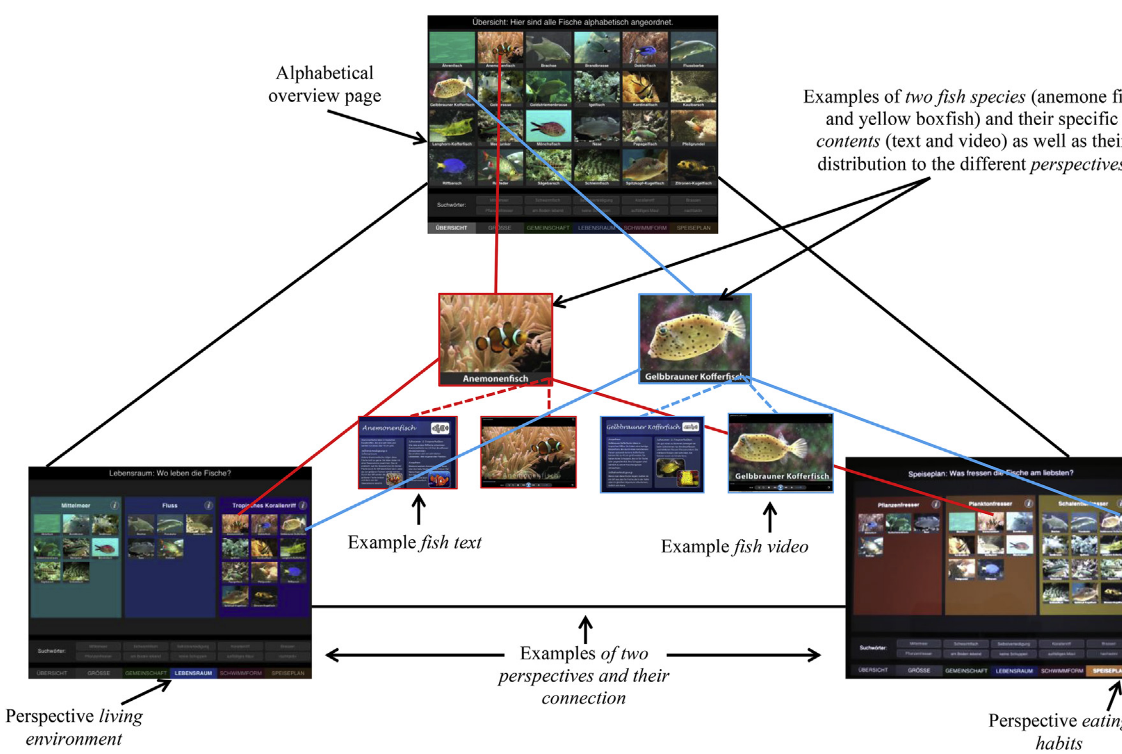


**Fig. 3.** Extract of the structural associations between two exemplary fish (anemone fish and yellow boxfish) and three exemplary perspectives (alphabetical overview, living environment, eating habits). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

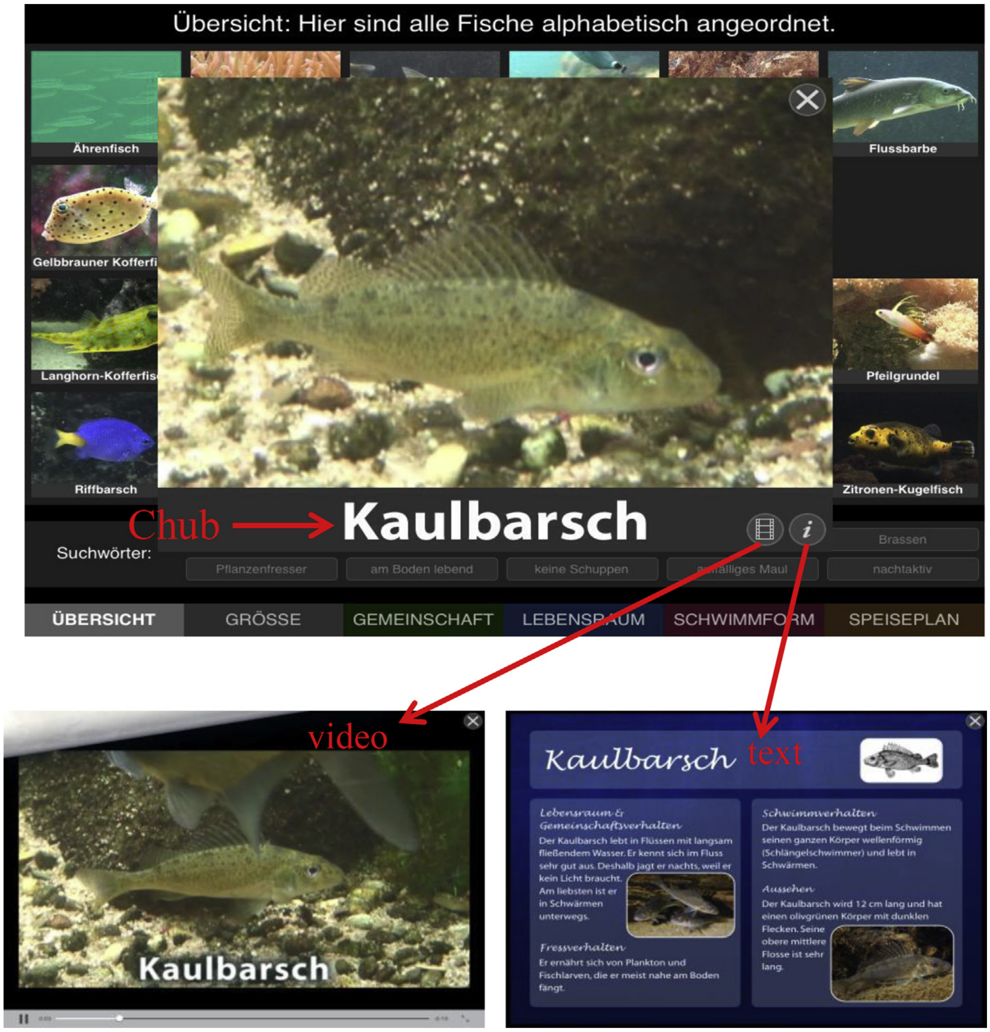


**Fig. 4.** Overview page of the MHE with the picture of the chub enlarged. Clicking on one of the two hyperlinks in the bottom right corner of the picture allows the user to either read additional text or watch a video about the chub.

processing, and irrelevant processing. Each of these analysis steps including log file examples will be described in detail in the appendix.

Applying the rule-matching algorithms specified for all exploration tasks to all action sequences in the log files resulted in a decision, for each action, about whether the action was associated with on-task or off-task navigational behavior, and whether it was related to perspective or content processing. This allowed us to classify all actions into one of the three navigational behaviors. Subsequently, we calculated the total time for perspective processing by summing up all on-task navigational behaviors associated with considering the fish from different angles to gain a conceptual overview of the fish topic (i.e., the total time spent on task-relevant conceptual perspective pages with and without filter use). Total time for content processing, by contrast, was calculated by summing up all on-task navigational behaviors associated with the processing of specific contents (i.e., task-relevant pictures, texts, and videos). Finally, irrelevant processing time was calculated by including all navigational behaviors that could not be associated with solving an exploration task (e.g., watching irrelevant videos, or applying irrelevant filters).

### 2.3.2. Exploration performance

The exploration tasks were not only implemented to guide and encourage children's exploration of the learning environment, but also served as dependent variables for their exploration performance during the learning phase. The exploration tasks (21 items; $\alpha = 0.74$) asked the children either to find information about specific fish (e.g., “What is the living environment of the breams?”) or to compare and interrelate different fish with each other (e.g., “Which features differ between nase fish and surgeon fish?”). The children's answers to these questions were scored by two blind and independent raters as correct or incorrect based on a sample solution (Cohen's kappa was $\kappa = 0.92$).

### 2.3.3. Learning outcomes

Subsequent to the learning phase, a posttest including *inferential questions* and *scientific transfer questions* was administered to the children to measure their learning achievement. The inferential questions (11 items, $\alpha = 0.59$) asked the children to combine different facts from their recently acquired fish knowledge and to subsequently draw conclusions (e.g., “Which fish do not need a well-lighted place for their aquarium? Why?”). The scientific transfer questions (seven items, $\alpha = 0.83$), by contrast, asked the children to transfer the conceptual knowledge that they had acquired about fish biodiversity (i.e., the relation between different perspectives or different fish) to another subject area; namely, to fantasy animals called *kornikels*. More specifically, this task challenged them to


**Fig. 5.** "Swimming style" perspective page ("What is the swimming style of the fish?") from the MHE with an activation of the filter "plant eaters" and the nase fish and the surgeon fish circled in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

consider the kornikels from different perspectives. However, in contrast to the MHE about fish species, the information about kornikels was provided as paper-based text so that its inherent multifaceted structure was not as visible as in the MHE. Analogously to the fish materials, the different kornikel species also varied with regard to their eating habits, their social behavior, their living environments, and so on. The children had to use this information to solve complex tasks that challenged them to relate different pieces of information about the kornikel species and to subsequently draw elaborated and scientific inferences (e.g., "How could you prove that the swimming kornikels are the most aggressive of the kornikel species?"). The children's free answers to the inferential and scientific transfer questions served as dependent variables representing their learning performance and were again scored by two blind and independent raters as correct or incorrect based on a sample solution (Cohen's kappa was $\kappa = 0.88$ for the inferential questions and $\kappa = 0.83$ for the scientific transfer questions).

#### 2.3.4. *Working memory measures*

Children's spatial WM capacity was measured with the spatial span task (see Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000). In particular, we used an adapted version of this task from Vock's (2005) working memory battery for children (see also Kornmann, Zettler, Kammerer, Gerjets, & Trautwein, 2015; Vock & Holling, 2008). The spatial span task (15 items, $\alpha = 0.79$) contained figural material, namely, black and white patterns shown in a $3 \times 3$ matrix. The children had to memorize these patterns and simultaneously rotate them mentally, 90° either to the right or left. After a sequence of between one to four patterns, the children had to specify what the rotated patterns would look like on a white matrix. All items including two to four patterns were scored on a subpattern level. That is, a ratio of "number of correctly remembered and rotated patterns"/"number of patterns overall" was used. For instance, when two patterns were presented, children could get a score for this item of 0 (no pattern correctly remembered and rotated), 0.5 (1 pattern correctly remembered and rotated), or 1 (both patterns correctly remembered and rotated). Similarly, the possible scores for items with three patterns were 0, 0.33, 0.66, and 1, and for items with four patterns 0, 0.25, 0.50, 0.75, and 1. Finally, the scores for all items were summed up, resulting in a potential score for the spatial span task for each child between 0 and 15. The reliability of this task ($\alpha = 0.79$) was comparable to the reliability of the spatial span task reported in the study by Kornmann et al. (2015; $\alpha = 0.74$) as well as by Vock and Holling (2008; $\alpha = 0.76$). Further information on the psychometric properties of this task is given in Vock and Holling (2008).

### 2.4. *Procedure*

The study comprised two sessions. In the first session (about 20 min), the spatial span task as well as a few demographic questions were administered to each child individually. Within 10 days, the second session with groups of four to 10 children took place (about 90 min). First, to familiarize the children with the navigational design of the upcoming MHE, a training environment about different countries structured in the same way as the learning environment was administered to them. The children were allowed to practice with the training environment until they felt confident about using it. Afterwards, the real learning phase about biodiversity of fish began. To ensure that all children had sufficient prior knowledge about the subject matter and could adequately cope with the upcoming task demands, they were presented with a short introductory film about fish (about 5 min). This film invited the children to take on the role of a fish keeper in an aquarium and provided them with information about fish diversity based on the different perspectives presented in the MHE (e.g., different living environments). Subsequently, the children worked individually in the MHE for about 45 min by dealing with the exploration tasks. Finally, after completing the learning phase, the children worked on the post-test comprising the inferential questions and the scientific transfer questions (about 20 min).

## 3. Results

Descriptive statistics for the three navigational behaviors (perspective processing, content processing, irrelevant processing), the spatial span task, the exploration performance (exploration tasks), and the learning outcomes (inferential questions, scientific transfer questions) are presented in Table 2.

### 3.1. The relation between spatial WM capacity, navigation, and performance

Table 3 presents correlational analyses for all three navigational behaviors, spatial WM capacity, the exploration tasks, the inferential questions, and the scientific transfer questions. Next, we will present the results according to the respective hypotheses.

#### 3.1.1. Hypotheses 1 and 2: spatial WM capacity, performance, and navigation

With Hypothesis 1, we predicted that spatial WM capacity would be positively related to exploration performance and learning outcomes in the MHE. As can be seen from Table 3, spatial WM capacity was related to performance on the exploration tasks ($r = 0.47$, $p < 0.001$), the inferential questions ($r = 0.37$, $p < 0.001$), and the scientific transfer questions ($r = 0.36$, $p < 0.001$), supporting Hypothesis 1.

Second, we hypothesized that spatial WM capacity would be related to perspective processing and irrelevant processing but not to content processing. As expected, spatial WM capacity was positively related to perspective processing ($r = 0.34$, $p < 0.001$) and negatively related to irrelevant processing ($r = -0.39$, $p = 0.001$). Moreover, spatial WM capacity was not related to content processing ($r = 0.08$, $p = 0.435$; see also Table 3), supporting Hypothesis 2.

#### 3.1.2. Hypothesis 3: navigational behaviors and performance

Hypothesis 3 predicted that perspective processing would be positively, irrelevant processing would be negatively, and content processing would not be associated with exploration performance and learning outcomes. To test this hypothesis, we computed three linear regression analyses with perspective processing, irrelevant processing, and content processing as independent variables and the exploration tasks, inferential questions, and scientific transfer questions as dependent variables (see Table 4). We z-standardized all variables beforehand to allow easier interpretation of the *B*-values. The linear regression analysis with the exploration tasks as the dependent variable was significant, $R^2 = 0.36$, $F(1, 95) = 17.71$, $p < 0.001$. Perspective processing was a significant positive predictor but not irrelevant processing or content processing. We found the same pattern of results when using the inferential questions as the dependent variable, $R^2 = 0.22$, $F(1, 95) = 8.58$, $p < 0.001$. Perspective processing significantly predicted learning performance but irrelevant processing and content processing did not. Analogously, the linear regression analysis for the scientific transfer questions was also significant, $R^2 = 0.14$, $F(1, 95) = 5.21$, $p = 0.002$. Perspective processing again was a significant positive predictor but not irrelevant processing or content processing. In sum, these results partially supported Hypothesis 3. As expected, we found that perspective processing was positively associated and content processing was not associated with exploration performance and learning outcomes. However, we did not find irrelevant processing to have an increment in explaining variance in exploration performance and learning outcomes over and above perspective processing. Still, we found irrelevant processing to be negatively correlated with exploration performance and learning outcomes when considered solely (see Table 3).

#### 3.1.3. Hypothesis 4: the mediating role of perspective processing

Finally, we aimed to investigate whether the positive relation of spatial WM capacity with exploration performance and learning outcomes might be explained by the use of perspective processing. To this end, we conducted mediation analyses as described by Hayes (2013). In total, three models with each of the three performance measures (exploration tasks, inferential questions, and scientific transfer questions) as dependent variables were tested.

In Model 1, we examined the relation between spatial WM capacity and exploration tasks while controlling for perspective processing. Although the relation between spatial WM capacity and exploration tasks did not disappear ($B = 0.30$, $SE_B = 0.08$, $p < 0.001$), confidence intervals produced by the bootstrapping analyses showed that the indirect effect through perspective processing was significant ($B = 0.17$, $SE_B = 0.05$; CI 95% [0.08, 0.28]).

In Model 2, we examined the relation between spatial WM capacity and the inferential questions while controlling for perspective processing. Again, the relation between spatial WM capacity and the inferential questions did not disappear ($B = 0.24$, $SE_B = 0.09$, $p < 0.05$). Still, confidence intervals produced by the bootstrapping analyses showed that the indirect effect through perspective processing was significant ($B = 0.13$, $SE_B = 0.04$; CI 95% [0.06, 0.24]).

Finally, in Model 3, we examined the relation between spatial WM capacity and the scientific transfer questions while controlling for perspective processing. Comparable to Model 1 and 2, the relation between spatial WM capacity and the scientific transfer questions did not disappear ($B = 0.27$, $SE_B = 0.10$, $p < 0.05$) while the confidence intervals produced by the bootstrapping analyses indicated a significant indirect effect through perspective processing ($B = 0.89$, $SE_B = 0.04$; CI 95% [0.02, 0.19]).

Taken together, the navigational behavior of perspective processing did not completely mediate the relation between spatial WM capacity and performance. Still, the indirect effects through perspective processing were significant both for the exploration tasks and the learning outcomes. Thus, although spatial WM capacity itself still had a strong independent influence on performance, perspective processing could at least explain part of this

**Table 2**
Mean scores (standard deviations) for the three navigational behaviors (perspective processing, content processing, irrelevant processing), the spatial span WM task, the exploration performance (exploration tasks), and the learning outcomes (inferential questions and scientific transfer questions).

| Type of measure (unit/range) | | *M* (*SD*) ($N = 97$) |
|---|---|---|
| Navigational behaviors | Perspective processing (in s) | 936.65 (423.08) |
| | Content processing (in s) | 620.20 (262.51) |
| | Irrelevant processing (in s) | 988.07 (417.24) |
| Spatial WM capacity | Spatial span task (1–15) | 8.50 (2.68) |
| Exploration performance | Exploration tasks (percentage correct) | 47.66 (16.10) |
| Learning outcomes | Inferential questions (percentage correct) | 41.72 (19.82) |
| | Scientific transfer questions (percentage correct) | 37.89 (32.97) |

**Table 3**
Intercorrelations between the three navigational behaviors, spatial WM capacity, the exploration tasks, the inferential questions, and the scientific transfer questions.

| Type of measure | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1) Perspective processing | – | | | | | | |
| 2) Content processing | −0.24* | – | | | | | |
| 3) Irrelevant processing | −0.66** | −0.31** | – | | | | |
| 4) Spatial WM capacity | 0.34** | 0.08 | −0.39** | – | | | |
| 5) Exploration tasks | 0.60** | −0.07 | −0.46** | 0.47** | – | | |
| 6) Inferential questions | 0.46** | −0.11 | −0.33** | 0.37** | 0.71** | – | |
| 7) Scientific transfer questions | 0.35** | 0.05 | −0.31** | 0.36** | 0.63** | 0.64** | – |

*Note.* $N = 97$.
*$p < .05$. **$p < .01$.

**Table 4**
Results of the linear regression analyses for the three navigational behaviors predicting performance.

| | $B$ | $SE_B$ | $t$ | $p$ |
|---|---|---|---|---|
| *Exploration tasks* | | | | |
| Perspective processing | 0.54 | 0.14 | 3.81 | <0.001 |
| Content processing | 0.03 | 0.11 | 0.26 | 0.796 |
| Irrelevant processing | −0.10 | 0.15 | −0.66 | 0.513 |
| *Inferential questions* | | | | |
| Perspective processing | 0.41 | 0.16 | 2.63 | 0.010 |
| Content processing | −0.03 | 0.13 | −0.25 | 0.803 |
| Irrelevant processing | −0.07 | 0.16 | −0.40 | 0.688 |
| *Scientific transfer questions* | | | | |
| Perspective processing | 0.36 | 0.16 | 2.16 | 0.033 |
| Content processing | 0.12 | 0.13 | 0.93 | 0.354 |
| Irrelevant processing | −0.04 | 0.17 | −0.24 | 0.808 |

association, partially supporting Hypothesis 4.

## 4. Discussion

The present study investigated the interplay of spatial WM capacity, navigational behaviors, and exploration performance and learning outcomes in an MHE. Importantly, we addressed this issue in a sample of fourth-graders which is so far a relatively unexplored, but highly interesting population concerning MHEs (given the inflexion point concerning reading comprehension; cf. Kaplan, 2013). More specifically, we first aimed to replicate the positive association between spatial WM capacity and hypermedia learning in this age group. In line with earlier studies (e.g., Pazzaglia et al., 2008), our results revealed that spatial WM capacity was strongly associated with exploration performance (i.e., solving exploration tasks) and learning outcomes (i.e., answering inferential questions and scientific transfer questions). To conclude, the positive effect of high (spatial) WM resources on hypermedia learning can be generalized to fourth-graders working in MHEs.

### 4.1. WM capacity and navigational behaviors

More importantly, we explored the relation of spatial WM capacity and navigational behaviors in an MHE. Supporting our second hypothesis, we found that spatial WM capacity was positively related to perspective processing, whereas it was negatively related to irrelevant processing. Moreover, spatial WM capacity was not related to content processing. To conclude, children with high spatial WM capacity engaged in perspective processing more than children with low spatial WM capacity. Children with low spatial WM capacity, instead, engaged in more irrelevant processing and, thus, seemed to have difficulties assessing what was relevant for the task. Taken together, the executive control processes associated with (spatial) WM, such as switching attention between different perspectives (i.e., perspective processing) or focusing attention while inhibiting irrelevant information (i.e., avoiding irrelevant processing), seem to play a crucial role in effectively navigating an MHE.

### 4.2. Navigational behaviors and performance

Furthermore, we focused on the relations between the different navigational behaviors and all performance measures (exploration tasks, inferential questions, scientific transfer questions). As expected by our third hypothesis, perspective processing positively predicted performance, whereas content processing was not related to performance. Thus, the selection of conceptual overview pages to relate various contents across different perspectives represents an effective navigational behavior when exploring MHEs. By contrast, the mere processing of isolated content materials (although task-relevant) does not represent an effective navigational behavior in MHEs. As theoretically assumed, content processing might not be sufficient for facing the challenges of an MHE. Other than expected, irrelevant processing did not have an increment in explaining variance in performance over and above perspective processing, although it was negatively correlated with performance when considered alone (see Table 3). It is likely that its substantial negative correlation with perspective processing ($r = -0.66$, $p < 0.001$) overrode the effects of irrelevant processing. That is, both predictors had a high amount of overlapping variance. As perspective processing emerged as a stronger predictor of performance, it removed the variance from irrelevant processing so that the latter did not appear significant any more.

### 4.3. The mediating role of perspective processing

Finally, partly supporting our fourth hypothesis, perspective processing was revealed to partially mediate the relation between spatial WM capacity and students' performance in the exploration tasks and the learning outcomes. These mediation effects provide insights into the underlying processes that are responsible for the repeatedly found association between WM capacity and hypermedia learning (e.g., Pazzaglia et al., 2008). More precisely, the present results indicate that spatial WM capacity leads to more effective navigation, namely perspective processing, which in turn leads to higher exploration performance and learning outcomes. This finding is in line with previous studies that found navigational behaviors to mediate the relation between students' learning prerequisites and learning outcomes (Naumann et al., 2008; Salmerón & García, 2011). Specifically, Naumann et al. (2008) focused on the effect of a strategy training on learning outcomes in a hypertext setting in a sample of undergraduate students and demonstrated that this link was not only mediated by the quality of navigational behaviors (i.e., visits of relevant pages) but that this indirect effect was only positive for learners with high WM capacity or high reading skills. Similarly, Salmerón and García (2011) found in their study with sixth-graders that the relation between reading skills and comprehension in a hypertext setting about Romans was mediated by the navigational strategy of cohesive hyperlinking, that is, selecting links that are semantically related. These studies, along with our own study, show that a particular navigational behavior (i.e., cohesive hyperlinking, visit of relevant pages, or perspective processing) can maximize learning outcomes if specific learning prerequisites, such as high reading skills or high WM capacity, are present. For future studies it might be particularly interesting to investigate the interplay of such different learning prerequisites (e.g., reading skills and (spatial) WM capacity) in a sample of fourth-graders (or older children) and their differential influence on the navigational behavior of perspective processing in an MHE.

With regard to the present findings, however, it should be noted that perspective processing could explain only part of the relation between spatial WM capacity and performance. Thus, spatial WM capacity still influenced performance beyond this navigational behavior. It is likely that this is due to the domain-general part of WM (cf. Kane, Conway, Hambrick, & Engle, 2007) which is supposed to independently influence learning performance. Whereas the spatial part of WM might particularly influence students' navigational behavior, the domain-general part of WM (which can never be excluded from any WM task) might have influenced other learning processes such as information processing activities, which also strongly influence learning and comprehension (Kyllonen & Christal, 1990). Due to the richness of information in hypermedia environments, information processing activities—such as processing large amounts of information, integrating different kinds of information, and keeping the results in mind during subsequent processing steps (cf. Ericsson & Kintsch, 1995)—are particularly challenging in these environments, so that learners with high WM resources (including both spatial WM parts and general WM resources) might be more effective overall. Future studies should thus replicate and expand the current study by using different WM measures that also tap verbal and numerical materials in order to investigate the influence of general WM on learning performance and to disentangle it from the influence exerted by specific WM domains (i.e., spatial vs. verbal/numerical WM) in MHEs.

### 4.4. Limitations and outlook

Concerning potential limitations of the present research, it should be noted that the results of our study were based on correlational data. Thus, no direct causal inferences can be drawn concerning the relations between spatial WM capacity, navigational behaviors, and performance. In particular, we cannot take the results of the mediation analyses as conclusive evidence of causal effects but should interpret them cautiously. It might be possible that the perceived relations were confounded by unobserved variables that were not included in the analysis such as intelligence or socioeconomic status. Thus, the results of the mediation analyses can be taken only as an indication of how the effect of spatial WM capacity on performance might be explained. Still, our results provide unique and novel findings about the relations between fourth-graders' spatial WM capacity, their navigational behaviors, and their exploration performance as well as learning outcomes in an MHE. Nevertheless, future studies might build upon these findings by experimentally manipulating some central variables which would allow for causal interpretations. For instance, as a between-subject factor a different type of hypermedia environment or a different kind of task that does not involve perspective processing could be included. This might reveal whether the mediational links are moderated by this manipulation and thus could shed light on causal effects.

As another limitation, our inferential questions had a relatively low internal consistency estimate. This might be explained by the fact that the inferential questions required the children not only to make inferences but also to reactivate their acquired fish knowledge. That is, contrary to tests that deal with a more homogenous construct (e.g., personality traits or intelligence domains), knowledge tests comprise various multifaceted items to capture different and potentially independent aspects of a knowledge domain. For instance, a child may have understood the differences between river fish and tropical coral reef fish, thereby answering a corresponding question correctly. By contrast, he or she may have failed to understand how the different ivories of the breams are associated with their eating habits, thereby not receiving a point for a corresponding question. Such a pattern of answers may result in lower internal consistency. However, note that it is even possible that a higher internal consistency would have resulted in larger effects.

Also, note that we herein only focused on one cognitive variable that might influence effective navigation in MHEs, namely on spatial WM, which is considered as an important variable in the learning context (e.g., Alloway & Alloway, 2010; Seigneuric & Ehrlich, 2005). However, it is possible that other basic cognitive functions such as executive functions (see Miyake et al., 2000) might influence effective navigation in MHEs as well. Therefore, as a next step it might be interesting to focus on additional variables measured with other tasks (e.g., executive functions by tasks proposed in Miyake et al., 2000) in order to disentangle the influence each variable exerts on navigation. It is possible that other cognitive variables might influence effective navigation to a similar degree (or even more) than spatial WM and thus might be similarly (or even more) important in the context of MHEs.

Finally, it should be acknowledged that the present study focused on log files to shed light on the processes that underlie hypermedia exploration and learning. By conducting complex log file analyses, it was not only possible to determine the children's on- and off-task navigational processing but also to reveal different navigational behaviors that were highly predictive of hypermedia learning. Still, log files are limited as they cannot provide information about conscious intentions while processing. Future studies could thus additionally include other process measures (e.g., think-aloud protocols, eye-tracking), which might provide further insight into learners' processing (e.g., concerning their awareness of navigational behaviors or reasons for their navigational decisions).

### 4.5. Conclusion

Considering the present findings, spatial WM capacity appears to represent an important learning prerequisite when exploring MHEs, at least for the so far relatively unexplored population of fourth-graders. More precisely, spatial WM capacity not only seems to impact exploration and learning performances for this age group but also seems to be strongly associated with effective navigation in these environments, namely with perspective processing. Thus, according to the present findings, in order to benefit from MHEs, it seems not helpful to engage in isolated processing of task-relevant learning materials (content processing), but it is particularly important to explore the contents by selecting and comparing different perspective overview pages (perspective processing). However, only children with high spatial WM capacity seem to be able to apply this effective navigational behavior. Thus, MHEs should be implemented in a classroom only if the group of students consists of advanced learners, namely of students with high (spatial) WM capacities. For students with low (spatial) WM resources, instead, other types of learning environments (e.g., linearly structured environments) might be more suitable. This is in line with Cowan (2013) who claims that “For learning and education, it is important to take into account the basic principles of cognitive development and cognitive psychology, adjusting the materials to the working memory capabilities of the learner” (p. 22).

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## Appendix

In the following, a detailed description of each analysis step of our automatic log file analysis is provided.

*Raw representation of students' actions in the log files*

Each line in the log files represented one action of a student in the MHE by means of four parameters. These parameters were time stamp (h : min : sec), student identifier, type of action, and often an additional parameter, such as the name of a particular fish species or perspective or filter currently being considered. Possible actions (here printed in capital letters) were related to the opening (i.e., showing) and closing of content information (SHOW/CLOSE TEXT/PICTURE/VIDEO) and to the selection of one of the perspective displays or filters (SHOW PERSPECTIVE/FILTER). Line (1) to (3) present three example lines from log files with subjects taking actions (1) to retrieve a picture of the chub, (2) to see all fish species sorted by their living environment, and (3) to highlight all fish species that are plant eaters by means of a filter button.

| | | | | |
|---|---|---|---|---|
| (1) | 08 : 16 : 06 | *Subject* 1 | *SHOW PICTURE* | *Chub* |
| (2) | 14 : 21 : 18 | *Subject* 2 | *SHOW PERSPECTIVE* | *Living environment* |
| (3) | 08 : 40 : 40 | *Subject* 3 | *SHOW FILTER* | *Plant eaters* |

*Enriched representation of students' actions*

In a second step, we enriched the representation of students' raw actions, mainly by inferring additional information with regard to the specific situational context in which an action was taken. For instance, from analyzing actions prior to the action of retrieving a picture of the chub (or the action of applying the plant-eaters filter) it could be inferred, which perspective display was active when the picture was retrieved (or when the filter was applied). These pieces of information were important in order to be able to analyze the meaning of particular actions in the context of other actions. The enriched representation of students' actions resulted in six parameters, namely time stamp, student identifier, type of action, currently active fish species, currently active perspective, and currently active filter (if no filter was active the value of this parameter was set to NONE). Thus, if a subject retrieved a picture of the chub when the display showed the living environment perspective while the plant-eaters filter was active, the action representation could look like Line (4):

(4) 08 : 16 : 06 *Subject* 1 *SHOW PICTURE* *Chub* *Living environment* *Plant eaters*

*Action patterns*

In the next step we introduced pattern definitions that characterized particular types of actions more abstract and independent of their specific instantiations. First, we abstracted from the acting person and the time stamp of an action, yielding the following representation of an action pattern (Pattern P1) for which Line (4) would describe one instance:

*Pattern P1* : *SHOW PICTURE*, *Chub*, *Living environment*, *Plant eaters*

Second, we introduced higher-level action descriptions (e.g. SHOW CONTENT) that summarized different types of actions (e.g., showing text, picture, or video information with regard to a particular fish species). Accordingly, a more abstract action pattern than Pattern P1 could be Pattern P2:

*Pattern P2* : *SHOW CONTENT*, *Chub*, *Living environment*, *Plant eaters*

Third, we introduced a wildcard character (*) that may be substituted by all possible instantiations of the respective parameter. This step allowed defining even more abstract patterns when we were not interested in the value of certain parameters. The main purpose of this step was to define a pattern that matched when one or two specific parameters were present, such as reading or watching information about a specific fish, whereas other parameters, such as whether a filter was active or which perspective was chosen, were not important. Accordingly, Pattern P3 would represent actions of retrieving content information on the chub irrespective of the currently active perspective and a currently active filter:

*Pattern P3*: *SHOW CONTENT*, *Chub*, *, *

For instance, for one of the tasks given to learners in our study (“Where does the chub live?”, cf. Section 2.2.2) actions matching to pattern P3 would indicate relevant navigational behavior on a content-processing level.

By contrast, in case that a participant had chosen a perspective-processing strategy a different pattern would have appeared. Based on this strategy, relevant behavior would be to display all fish species organized by their living environment. Pattern P4 represents this behavior:

*Pattern P4* : *SHOW PERSPECTIVE*, *NONE*, *Living environment*, *NONE*

Matching the enriched representations of students’ actions (derived from the log files) against the patterns P1 to P4 was relatively simple. For example, pattern P3 would match to the action of Subject 1 in Line (4) or to any analogous action like retrieving a video on the chub as represented in Line (5):

(5) 09 : 16 : 06 *Subject* 1 *SHOW VIDEO* *Chub* *Living environment* *Plant eaters*

*Meaningful sequences of action patterns*

In the next step, action patterns were used to define meaningful sequences of action patterns that were the basis for classifying navigational behaviors as either perspective or content processing for a particular task. We defined a set of rules for each of the students’ tasks by specifying possible meaningful action sequences to accomplish this task. The rules were composed of patterns and could include order of patterns, counting (how often a pattern matched), and operators to logically connect patterns (e.g., or, not). For instance, the rule for detecting a meaningful action sequence matching the task of identifying the living environment of the chub (Rule R1), defined all action sequences as appropriate that satisfied the following constraints:

$$Rule\ R1:\quad P3\ or\ P4;\ \ repeat$$

That is, we wanted to see students either to retrieve any kind of content information on the chub (P3) or to select the living-environment perspective (P4).

These actions could be repeated multiple times, which enabled Rule R1 to capture the whole sequence of actions related to the task of identifying the living environment of the chub in order to quantify how long students spent on a task and in which processing mode.

The following example illustrates how the Rule R1 would be matched against the original log file by assigning Patterns (P3 to P4) to the individual actions in the log files and by matching the sequence of patterns occurring in the log files to the constraints defined by the rule. In this example the subject first showed a perspective processing strategy (P4), but then switched to a content-processing strategy (P3), which is in line with the constraints of Rule R1.

| | | | | |
|---|---|---|---|---|
| 14 : 21 : 18 | *Subject* 4 | *SHOW PERSPECTIVE* | *Living Environ.* | *P*4 |
| 14 : 21 : 54 | *Subject* 4 | *SHOW PICTURE* | *Chub* | *P*3 |
| 14 : 21 : 57 | *Subject* 4 | *SHOW TEXT* | *Chub* | *P*3 |

*Classifying action sequences*

The Rule R1 describing on-task behavior for the task of identifying the living environment of the chub provides an easy example of how on-task versus off-task navigational behavior (i.e., actions not matching P3 to P4 in line with the constraints of R1) could be defined. Moreover, the example also shows how perspective processing (P4) versus content processing (P3) could be distinguished. However, associating sequences of actions with a specific task was often more complicated in our study, in particular when different navigational strategies (indicative of perspective or content processing) implied sequences of multiple actions. For instance, one exploration task in our study challenged the children to compare two “plant eater” fish, namely the nase fish and the surgeon fish (see Section 2.2.2). This task could only be solved by engaging in a sequence of multiple actions and not by a single action alone as in the previous task. Thus, meaningful action sequences at the content-processing level would involve performing multiple alternating SHOW CONTENT activities with regard to the two fish. At the perspective-processing level, by contrast, we would have expected students to perform multiple SHOW PERSPECTIVE activities by which they would alternate between different perspectives (living environment, swimming style, size etc.) in order to find out how the two fish species differed under each of these perspectives. Nevertheless, in the nase fish versus surgeon fish task, we could use the same formalism as in the simple example above to define action patterns and meaningful sequences of action patterns related to the content-processing strategy and to the perspective-processing strategy.

For matching the content processing strategy, we defined meaningful sequences of three patterns that described, first, actions of retrieving content for the nase fish (P5), second, the same for the surgeon fish (P6), and third, the same for any other fish (which would be off-task behavior for this task; P7)).

*Pattern P*5 : *SHOW CONTENT*, *nase fish*, *, *
*Pattern P*6 : *SHOW CONTENT*, *surgeon fish*, *, *
*Pattern P*7 : *SHOW CONTENT*, *other fish than nase or surgeon fish*, *, *

Meaningful sequences indicating content processing were sequences of the first two patterns (P5 and P6) without substantial instances (longer than 10 s) of the third pattern (P7) in between.

For the perspective processing strategy we defined five additional patterns and meaningful sequences of these patterns (P8 to P12). The patterns described the selection of one of the four perspective displays (P9 to P12) as well as the activation of the plant eaters filter (as both fish, namely the nase fish and the surgeon fish, were plant eaters so that less irrelevant fish were visible when using this filter; P8).

*Pattern P*8 : *SHOW PERSPECTIVE*, *NONE*, *, *plant eaters*
*Pattern P*9 : *SHOW PERSPECTIVE*, *NONE*, *Living environment*, *plant eaters*(*optional*)
*Pattern P*10 : *SHOW PERSPECTIVE*, *NONE*, *Social behavior*, *plant eaters*(*optional*)
*Pattern P*11 : *SHOW PERSPECTIVE*, *NONE*, *Eating habits*, *plant eaters*(*optional*)
*Pattern P*12 : *SHOW PERSPECTIVE*, *NONE*, *Size*, *plant eaters*(*optional*)

Meaningful sequences described switches between the different perspectives (to compare the two fish species with regard to different dimensions), either with or without activation of the plant eaters filter (R2):

$$Rule\ R2:\quad P8(optional)\ and/or\ P9\ or\ P10\ or\ P11\ or\ P12;\ \ repeat$$

Applying the rule-matching algorithms specified for all exploration tasks to all action sequences in the log files resulted in a decision, for each action, about whether the action was associated with on-task or off-task navigational behavior, and whether it was related to perspective or content processing. This allowed us to classify all actions into one of the three navigational behaviors. Subsequently, we calculated the total time for perspective processing by summing up all on-task navigational behaviors associated with considering the fish from different angles to gain a conceptual overview of the fish topic (i.e., the total time spent on task-relevant conceptual perspective pages with and without filter use). Total time for content processing, by contrast, was calculated by summing up all on-task navigational behaviors associated with the processing of specific contents (i.e., task-relevant pictures, texts, and videos). Finally, irrelevant processing time was calculated by including all navigational behaviors that could not be associated with solving an exploration task (e.g., watching irrelevant videos, or applying irrelevant filters).

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