

Modeling system thinking – assessment, structure  
validation and development

**Dissertation**

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**Kristina Fraune**

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Referent/Referentin: Prof. Dr. Ute Harms

Korreferent/Korreferentin: Prof. Dr. Jan Retelsdorf

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Margit & Ursel

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## Summary

Contributing to the demand of implementing complex system principles in science education to strengthen scientific understanding, the present thesis focuses at different aims in current system thinking research. Addressing the need to establish appropriate assessment tools, different assessment instruments were evaluated. A computer based Concept Mapping practice proved to be a promising extension to traditional questionnaire techniques, particularly enriching the structural visualization.

Further, regarding the need to characterize the structure of system thinking, complex system principles and emergent multilevel behaviour were transferred and constructed in form of an biological intervention unit ("The blue mussel in the context of the Wadden Sea ecosystem"), providing a comparable knowledge input in elementary and secondary school to evaluate system thinking in both grades. These investigations supported the underlying two-factorial theoretical model of system thinking (Sommer & Lücken, 2010) by providing valid conclusions concerning the model structure and construct stability for both class levels. This structural analysis offers an important contribution to the ongoing discussion about the dimensionality of system thinking. Moreover, it points to investigations concerning the exploration of elementary students' abilities to develop system thinking, corroborating suggestions about implementing complex system principles as early as possible (Assaraf & Orion, 2010; Evagorou et al., 2009; Sommer & Lücken, 2010) to prevent failure in system understanding (Jacobson & Wilensky, 2006). Owing to the two-factorial structure, the analysis of the internal relationship between structural and procedural system thinking tied in with a bidirectional theoretical assumption (Schneider, Rittle-Johnson & Star, 2011) and subsequently confirmed an iterative model structure. Due to the

fact that even implementing general cognitive abilities into the structural model didn't affect this structural pattern, this investigation provides important information for the development of system thinking.

In summary, these investigations offer diverse connecting factors being relevant both scientifically and educationally. The understanding of complex system principles is cognitively beneficial, concerning to scientific contexts but also to an employability framework. In educational contexts, the way of how students learn influences their knowledge structuring, determining the resulting knowledge pattern. Therefore, this connection should be noticed as an interlinked process concerning system thinking development. Consequently, an adequate understanding of system thinking development can contribute to curricula design and development, including teaching units that support students' system thinking appropriately thereby effectively preparing them for the demands of everyday life in 21<sup>st</sup> century.

## **Zusammenfassung**

Dieser Studie liegen verschiedene Ziele im Rahmen der aktuellen Forschung zum Systemdenken zugrunde, die an generelle Systemprinzipien zur Förderung naturwissenschaftlichen Verständnisses anknüpfen. Es besteht Bedarf im Bereich der Entwicklung geeigneter Messinstrumente, die den komplexen Systemstrukturen gerecht werden und eine valide Erhebung von Systemdenken zulassen, aber auch im Bereich der grundsätzlichen strukturellen Aufklärung des Konstrukts Systemdenken. Bezugnehmend auf die aktuelle Debatte über die altersabhängige Entwicklung von Systemdenken, wurden im Rahmen der vorliegenden Arbeit Instrumente entwickelt und auf ihre Eignung überprüft. Hierbei erwies sich eine computerbasierte Concept Mapping Methode als vielversprechende Ergänzung zu herkömmlichen Fragebogen-Testinstrumenten. Sämtliche Untersuchungen beziehen sich auf ein Referenzsystem, dessen Systemprinzipien und -prozesse in eine biologische Unterrichtseinheit („Die Miesmuschel im Ökosystem Wattenmeer“) übertragen wurden, um einen vergleichbaren Unterrichtsinhalt zwischen Grund- und weiterführender Schule zu gewährleisten. Das Systemdenken wurde unter zusätzlicher Kontrolle genereller kognitiver Fähigkeiten erfasst. Diese Erhebungen trugen zur Bestätigung des hypothetischen zweifaktoriellen Modells zum Systemdenken (Sommer & Lücken, 2010) bei und lieferten ein stabiles empirisches Fundament für beide Klassenstufen. Mit dem Ergebnis der zweifaktoriellen Struktur leistet die Strukturanalyse einen wertvollen Beitrag zur derzeitigen Diskussion über die Dimensionalität des Systemdenkens. Die Ergebnisse bestärken Empfehlungen zur frühestmöglichen Einführung allgemeiner Systemprinzipien bereits in der Grundschule (Assaraf & Orion, 2010; Evagorou et al., 2009; Sommer & Lücken, 2010), um fehlerhaftem Systemverständnis vorzubeugen (Jacobson & Wilensky,

2006). An die Aufklärung der zweifaktoriellen Struktur waren anschließend Analysen zur Ermittlung der internen Beziehung zwischen strukturellem und prozeduralem Systemdenken geknüpft. Basierend auf einer theoretischen Annahme einer bidirektionalen Beziehung (Schneider, Rittle-Johnson & Star, 2011) konnte eine iterative Modellstruktur bestätigt werden, die auch unter Einbeziehung der generellen kognitiven Fähigkeiten stabil blieb. Zusammengefasst bieten die vorliegenden Ergebnisse sowohl für die Forschung als auch für den Unterricht diverse Anknüpfungspunkte. Das Erfassen und Anwenden von Systemprinzipien ist kognitiv herausfordernd und fördert das Verständnis komplexer Phänomene sowohl im naturwissenschaftlichen, als auch im lebensweltlichen Kontext. Die Art, wie Schülerinnen und Schüler lernen, beeinflusst ihre Wissensstruktur. Dieser Prozess ist eng verknüpft mit der Entwicklung von Systemdenken. Ein adäquates Verständnis der Entwicklung von Systemdenken kann zu einem curricularen Design beitragen, das Systemdenken fördern und damit die Schüler effektiv auf die Herausforderungen des 21ten Jahrhunderts vorbereiten kann.



# **MODELING SYSTEM THINKING – ASSESSMENT, STRUCTURE VALIDATION AND DEVELOPMENT**

Contemporary science education research claims for a sufficient comprehension of scientific phenomena in terms of complex systems principles. Understanding complex systems requires mastery of concepts such as feedback, nonlinearity, time delays, and is usually counterintuitive and poorly understood, yet. Therefore, system thinking as an adequate understanding of scientific systems is of central interest of science education. To date, a growing complexity and intransparent development of global ecologic, economic and social problems is challenging our available knowledge to generate appropriate solutions. The adequate handling of such complex systems requires an adequate understanding of systemic processes, which is rooted in a sufficient encouragement of system thinking already at school. The perception of time related and feedback-loop processes as fundamental system characteristics will have an important impact on our orientation and decision-making in complex scientific, ecologic, economic and social systems in reality. Since there is still an immense need to clarify the central characteristics of system thinking, this Dissertation is focusing on an empirical approach to identify the structure and development of this construct. Based on a theoretical model of system competence, three studies were conducted to investigate appropriate assessment practices and to evaluate the validity of system thinking's theoretical model. Moreover, a comprehensive teaching unit for both elementary and secondary school

students was developed to provide comparable background knowledge in terms of a biological ecosystem.

## **1. System thinking research**

Based on different system-approaches that refer to the holistic analysis of a system's structure, function and behavior, the relevant roots for system thinking will be presented in the following chapter. On the basis of current perceptions the principal ideas of system thinking are elaborated to offer a precise insight into the ability construct of system thinking.

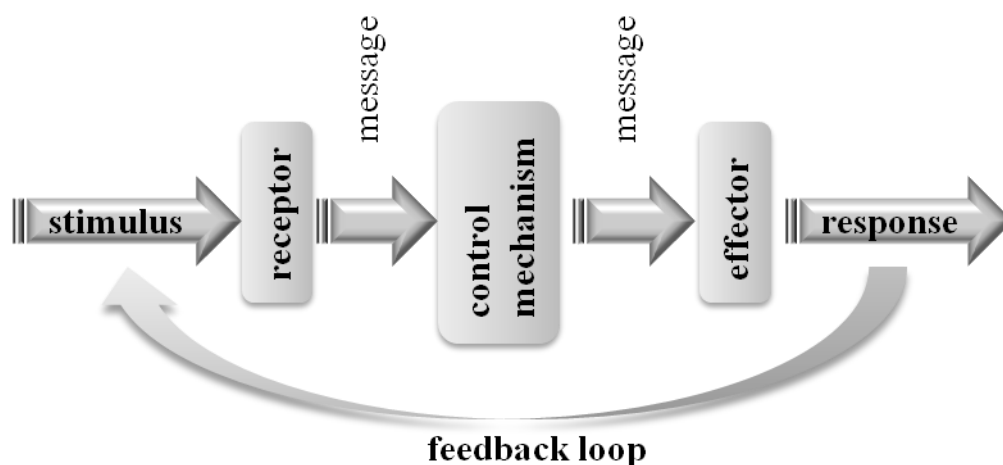
### **1.1. Different theoretical sources for a coherent system understanding**

The term "system" is widely used as concept that is applied by diverse scientific domains such as social systems, economic systems, mathematical systems, technological systems or biological systems. Consequently, there is no coherent system theory leading into one capacious definition. Diverse suggestions range from cybernetic roots (Wiener, 1948) to sociologic theories (Parson, 1963; Habermas & Luhmann, 1974), and biologic angles (Vester, 1997).

The initial phase for the development of "system thinking" was closely related to computer science and **Cybernetics**, substantially promoted by Norbert Wiener, who combined technical and biological sciences on the base of theoretical concepts (Wiener, 1948). The central aspect of Cybernetics is the information of a concept. For the first time, the principle of feedback-loops as nonlinear cause and effect relations was introduced as fundamental idea behind system properties. The field of Cybernetics basically refers to organizational patterns in networks like living systems and their feedback cycles. With regard to biology, the concept of self-regulation is an

essential aspect for cybernetics (Fig. 1). Self-regulation in biology can be referred to as process in which specific elements form their internal pattern to maintain a stable and relatively constant condition. As an example, living systems are able to balance their equilibrium state by feedback regulations. The central aspects of Cybernetics concerning living systems are the following:

- “Living systems can maintain a dynamic equilibrium by self-regulation through feedback mechanisms.
- Living systems can be part of an organized pattern that constitutes a control circuit maintaining a dynamic equilibrium.” (Verhoeff, 2003, p.41)



**Figure 1:** Concept of a system according to cybernetics (Verhoeff, 2003). Focusing on a feedback cycle, this model emphasizes the communication between elements and sub-systems within a system.

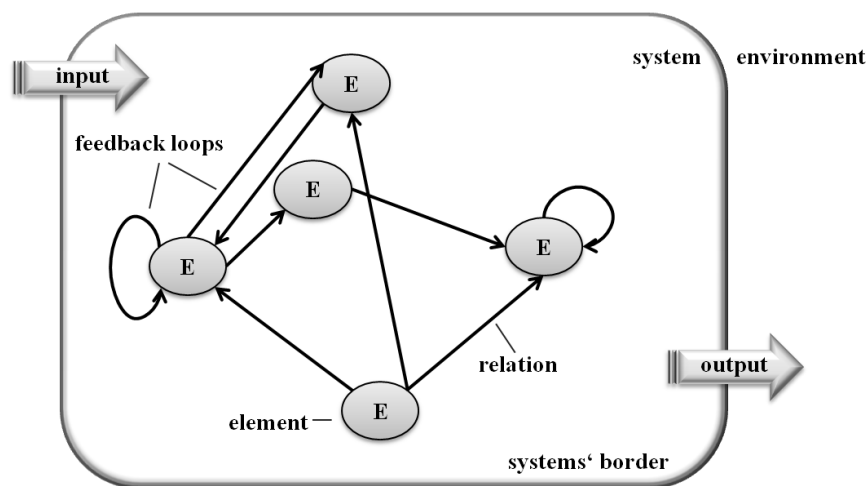
Approximately at the same time, Ludwig von Bertalanffy, a theoretical biologist, initially drew a bow from a system concept to the study of life (von Bertalanffy, 1950): “Every organic form is the expression of a flux of processes. It persists only in a continuous change of its components. Every organic system appears stationary if considered from a certain point of view; but if we go a step deeper, we find that this maintenance involves continuous change of the systems of next lower order: of

chemical compounds in the cell, of cells in multicellular organisms, of individuals in super individual life units.” (Von Bertalanffy, 1950, p. 27) His considerations on organismic patterns in biology paved the way for **General System Theory (GST)**. The focus of General System Theory was the principle behind a system instead of systems information as in Cybernetics. “An open system may attain (certain conditions presupposed) a time-independent state where the system remains constant as a whole and in its phases, though there is a continuous flow of the component materials” (von Bertalanffy, 1950, p. 23). Moreover von Bertalanffy (1950) referred to an open system perception by interpreting natural systems by claiming for a new system oriented scientific discipline based upon the following theoretical assumptions:

- The analytic and linear approach, usually applied in the field of sciences, is not sufficient regarding the complex and non-linear behavior of phenomena.
- Understanding a complex systems’ intertwined and multilevel emergence refers to all possible relations within a system. Therefore, the fundamental emergence of a system may be concealed by separating elements or examining discrete parts of a system.
- Different systems with various origins might be framed and understood through general system principles.

Thus, GST deals with fundamental system principles, counting for systems in general, to derivate elements and their interactions. The idea behind is to establish appropriate “in vitro” models that offer valuable clues concerning systems’ function and development. In doing so, such models function as an instrument to generate predictions and to simulate cause and effect relations within a system. Concerning GST, two main aspects can be defined as forming a systems’ structure: system

elements and system elements' relations (Bossel, 1987). Bossel (1987) modeled his general concept of systems in terms of a “causal loop diagram” with knots forming systems' elements and arrows forming system elements' relations (Fig. 2). Moreover, every system can be defined through a systems' border, separating the system from the surrounding environment.



**Figure 2:** Concept of a system according to Bossel (1987). By stressing the openness of a system, this model accentuates the dynamic and complex relations within a systems' border.

A third source of theoretical origin for system thinking is **Dynamic Systems Theory** (Verhoeff, 2003). This approach is closely related to thermodynamics, mathematics and fundamental process development within complex systems. Contrary to General Systems Theory, Dynamic Systems Theory points out the non-equilibrium state of open systems that is responsible for spontaneous development of more complex emergence. This especially contributes to evolutionary changes in biological systems. If there is an input of energy into a system a new system organization may evolve including a more complex system emergence. In doing so, Dynamic System Theory focuses on so called “attractor states” of a system (Thelen & Smith, 1994) that are referred to as all possible modes a system is able to develop to including the

whole range from stable to unstable conditions. From this point of view evolutionary development in a living system can be understood as change of the attractor state.

The following theoretical assumptions can be outlined on Dynamic System Theory:

- Living systems are able to develop more complex forms of organization by changing their attractor state.
- The emergent properties of a system as a result of continuous energy flow of the individual system parts sustain a non-equilibrium state.

These three theoretical approaches offer an outline on the development of system thinking. They present different insights either into a structural, organizational or developmental aspect of living systems. Concerning general legalities to elaborate a deep understanding of a system every three perceptions provide important characteristics. Resulting from these multiple perspectives, system thinking, on a general level, can be considered as ability to gain a capacious understanding of systems.

Based on these system theories, various scientific disciplines arose to model properties and developmental behaviors of for example social, technological, and natural systems. Therefore, this subject has been studied with different foci and intentions (Kim, 1999; O'Connor & McDermott, 1997; Penner, 2000).

But, since those theoretical foundations may lead to the assumption that almost everything might be considered as a system, a basic definition of the term “system” seems to lack any content. Consequently, a detailed analysis of every system is necessary if focusing on a preferably fitting model of the real system. In doing so, one has to consider the following questions:

- Which are the central elements forming a systems' emergence?
- Which relations have to be considered?

- Where to define the systems' border?

Thus, every characterization of a system can be considered as kind of modeling process. Identifying of elements, relations and systems' border is fundamentally influenced by the modeling purpose or the aim in view of a systems' analysis. Moreover, understanding a system is a constant shift from analysis to synthesis. Fundamentally, discrete elements and sub-systems have to be analyzed regarding their function and properties. Subsequently, those findings have to be interpreted in the context of the whole systems' emergence.

Basically, particular differentiations concerning a systems' habit can be made. The following differentiations can be carried out:

*open systems*       $\longleftrightarrow$       *closed systems*

*complex systems*       $\longleftrightarrow$       *plain systems*

*dynamic systems*       $\longleftrightarrow$       *static system*

As a consequence of investigating biological systems, this work focuses on complex and dynamic systems. For a detailed view on the other system specifications see Strohner (1995). As a basic principle, biological systems can be characterized as being **open**. This is due to a constant transfer of energy throughout the border of the system and factors that influence the system, respectively. Depending on whether factors affect from the out- or the inside of a system, they will be described as exogenous (affect from the outside) or endogenous (affect from the inside) factors (Hiering, 1988). Of course, the factors' attribution is relative, depending on the point of view. Therefore, the same factors can be considered as exo- or endogenous.

**Dynamic** systems can be characterized through a change over time. As outlined above open systems are affected by factors acting from the out- or inside. This is associated by a constant modification. Hence, a systems' development is of essential interest regarding the control and regulation options, respectively. These internal regulations receive their stimuli from various different components, interacting simultaneously with mainly implicit connections, altogether forming a multilevel net structure that is characteristic for **complex** systems (Eilam, 2012; Jacobson, 2001). To precisely quantify "complex" and "dynamic" as characteristic attributes is not only difficult but also of little value, since it is due to each systems' context, structure and of course to the viewers purpose and understanding, too. Understanding a complex system requires cognitive abilities in feedback-loop, dynamic, and forms of scientific thinking (Richmond, 1993). Actually, the attribute "complex" is used for a system that exceeds the viewers' cognitive capacity concerning the understanding of its conditions and their development. Nonetheless, there are five general aspects that compose complex and dynamic systems (Dörner 1996):

First "**side effects**" that are due to the fact that every real system is closely connected to surrounding systems. Every transformation does not have only one effect. It affects the internal system process but may also have an external impact. Second, those impacts may in turn constantly develop and appear as "**distant effects**". Third, "**down time**" or time delay may emerge from such effects and lead into time delay of particular processes. Fourth "**weak causal relations**" for example apparently minor effects, which cause substantial changes. As a result associated complex feedback loop regulations escalate and cause an immense "**nontransparent**" complexity that is the main attribute of complex and dynamic systems since their development is mainly invisible and remains more or less hidden.



In summary, complex and dynamic systems are composed of interdependent and interacting components, that either can be physical like objects or intangible like processes, information flows, relationships, feelings, values or beliefs (Anderson & Johnson, 1997). Their emergence is characterized by multiple feedback processes, including positive and negative feedback regulation, time delays, nonlinearities, and accumulations (Sterman, 2002). Referring to a systems emergence, “this group of interacting, interrelated or interdependent parts that form a complex and unified whole must have a specific purpose, and in order for the system to optimally carry out its purpose all parts must be present. Thus, the system attempts to maintain its stability through feedback. The interrelationships among the variables are connected by a cause and effect feedback loop, and consequently the status of one or more variables, affects the status of the other variables. Yet, the properties attributable to the system as a whole are not those of the individual components that make up the system” (Assaraf & Orion, 2005, p. 519-520).

These characteristics above illustrate aptly the challenges when handling with complex systems’ components, emergence and properties. On the one hand the everyday life is shaped by manageable systems with short time delay as the effect appearing directly and visibly like the handling of a car. On the other hand, given the present problems regarding ecologic, economic and social systems the environment is going to be more complex and intertwined although there is as many data of the world as never have been before. That imposes immense challenges for us nowadays and in the future, we have to revise our traditional way of thinking and problem solving. Moreover, we have to complement the linear-causal analysis through an adequate system thinking to prevent wrong or insufficient solutions. This consequently is closely tied in with an appropriate adoption at the phase of

education. Focusing on an adequate handling with complex systems, the understanding of systems properties and emergence should lead to a suitable question-posing. Especially with respect to biology education, the examination with natural resources and global consequences especially meets a sense of responsibility that is highly relevant in an educational context (Vester, 1997). Elaborating decision strategies and evaluating feedback-loop relations might particularly improve the area of education for sustainable development. These strategies in turn can be integrated across a number of science domains (Goldstone & Wilensky, 2008).

Defining the objectives gives rise to fundamental skills that have to be developed in the context of system thinking. These main characteristics will be carried out in the next chapter.

## **2. Empirical fundament for system thinking characterization**

The following section will clarify the base of system thinking's characterization. Central aspects of these investigations serve as empirical fundament, pioneering the research hypothesis of this thesis. A short summary at the end of each subsection will determine the open questions resulting from this actual research providing a starting point for the research questions of this thesis.

### **2.1. Empirical foundation of Evaluating and Assessing System Thinking**

Relating to science education, investigations on system thinking have increased in the past decades, which can be traced back to more suitable simulation tools that have been developed to better predict systems' development and behaviour (Boersma, Waarlo & Klaassen, 2011). As system thinking is supposed to

be an important ability concerning complex problem-solving and decision supporting (Hogan, 2000), it becomes even more important in the context of employability, because all citizens “must deal with challenging social and global problems in the 21<sup>st</sup> century” (Jacobson & Wilensky, 2006, p.11). The broad agreement on the importance of system thinking particularly in educational contexts generates a big variety of assessment settings to evaluate this ability. Consequently, the methodological ways to assess system thinking are as multifaceted as the ability construct itself is. A variety of assessment tools has been established for different points of interests, contents, numbers of probands and assessment periods. Therefore, different approaches were used to capture a complex ability construct like system thinking profoundly. Questionnaires came into operation, used solely (Evagorou, Kostas Korfiatis, Nicolaou, & Constantinou, 2009; Jacobson, Kapur, So & Lee, 2011; Riess & Mischo, 2010; Sommer & Lücken, 2010) and in combination with interviews (Assaraf & Orion 2005; Hmelo-Silver, Marathe & Liu, 2007; Verhoeff, 2003). Moreover, videotaped classroom discussions were applied to precisely document the development of system thinking (Assaraf & Orion, 2010).

However, the empirical indications point to the necessity for establishing assessment tools that could address the multilevel system characteristics. Moreover, there is need to focus at the implementation of large scale evaluations. Particularly, the idea of an appropriate way to better illustrate students’ conceptual understanding led to the implementation of mapping tools (Hmelo-Silver et al., 2007; Sommer & Lücken, 2010). Concept maps were developed to understand students’ knowledge development, particularly to follow possible changes in patterns of scientific knowledge (Novak & Gowin, 1984). In doing so, they function as external representations of knowledge structures. Since complex biological phenomena are

nonlinearly organized, the external representation of mental models is a helpful approach to the multilevel structure that biological phenomena include (Boulter & Buckley, 2000; Buckley & Boulter, 2000). Moreover, from a constructivist perspective, concept maps enable an insight into the structuring and restructuring of knowledge, the identification and eliciting of elements, links and concepts. In this way, concept maps are useful tools to promote students' knowledge integration and to improve complex system understanding by highlighting essential concepts (Nowak & Gowin, 1984) that in turn can improve the comprehension of commonalities across various domains (Novick & Hmelo, 1994).

Concerning the commonalities of concept mapping (CM) and system thinking, they both contribute to the concepts of structure, hierarchy and dynamism, which are substantiated by findings, that the number of elements, their relations and structure of concept maps is a reliable range for assessing students' system thinking (Odom & Kelly, 2000; Songer & Mintzes, 1994). Nonetheless, there is no general agreement about the appropriate concept mapping practice to assess system thinking. In science education research, different types of concept mapping practices are evaluated, characterized by the medium (computer based or paper-pencil based) used to construct the map and the degree of directedness of the concept mapping practice (highly directed CM practice: concepts and linking words are given; nondirected CM practice: concepts and linking words are withheld; Ruiz-Primo, 2004). Research findings show that computer based mapping offers easy manipulation through the dynamic linking of concepts (Anderson-Inman & Zeitz, 1993; Plotnick, 1997) that effectively supports the process of constant restructuring, as mentioned above and result in a considerably higher complexity than paper-pencil

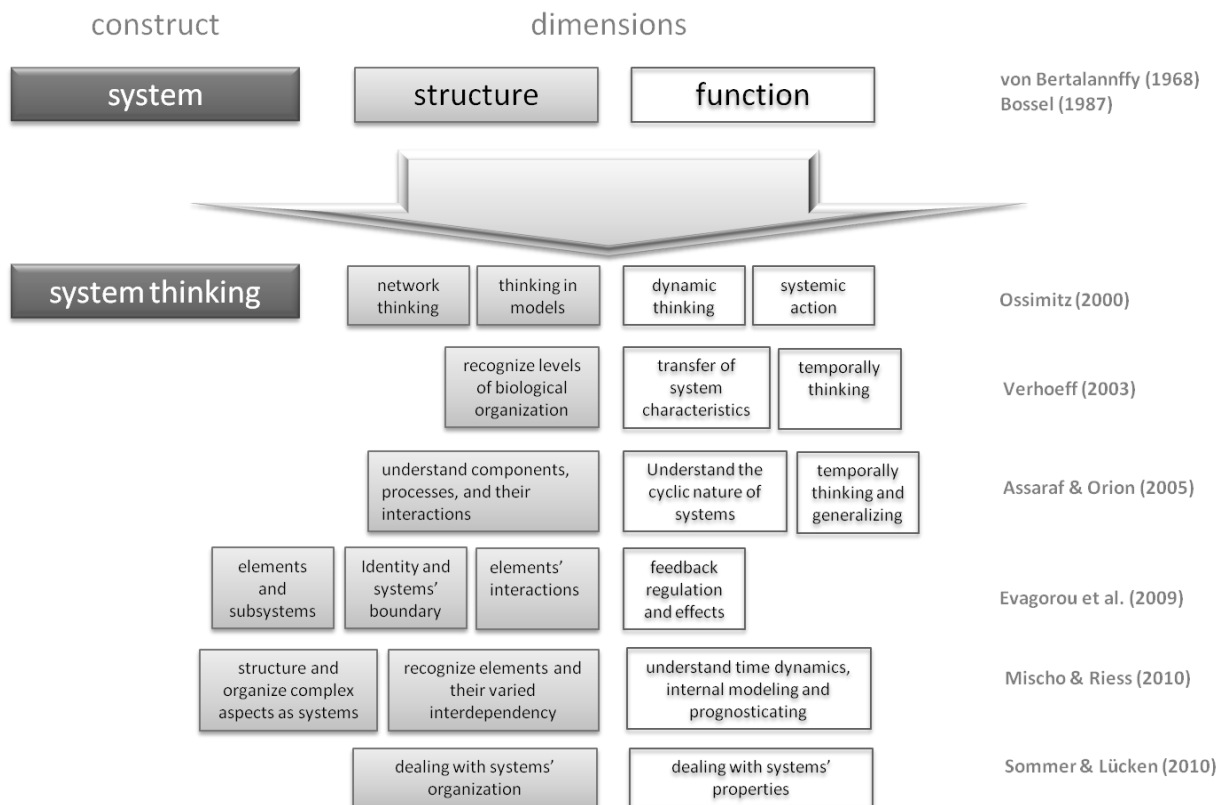
mapping. On the other hand, computer handling also might be too challenging for elementary students.

Consequently, there is explicit need to investigate appropriate concept mapping practices for system thinking assessment, especially in terms of large-scale assessments.

## **2.2. Empirical foundations for the construct structure of System Thinking**

Understanding the process of students' system thinking development takes the understanding of the internal structure of system thinking for granted. Especially the dynamic and intertwined system structure requires a wide amount of cognitive abilities (Jacobson, 2001). As mentioned above, general systems theory offers a structural framework for systems by (1) an organizational attribute (compassing systems identity formed by systems components) and (2) a functional attribute (resulting from interactions of the latter) (von Bertalanffy, 1968). Bossel (1987) pointed to this structural characterization by determining the structure of a system as the pioneering factor for systems' function and thereby accomplished the circular systemic regulation. Other findings drew a bow from such system characteristics to basic principles of system thinking, involving the understanding of the complex behavior of systems that leads to the emergent multilevel system structure (Anderson and Johnson, 1997, Ossimitz, 2000, Jacobson, 2001). All these findings agreed in interpreting system thinking as conglomerate of abilities to analyze system specific elements and their interrelationships, resulting in system specific properties, to understand cause- and effect-loops of dynamic processes and to prognosticate systemic effects and consequences regarding long time development (Booth Sweeny & Sterman, 2001; Kim, 1999; Maani & Maharaj, 2004). Assaraf & Orion (2005)

analyzed the structure of system thinking in a pattern of eight ability-aspects: 1. to identify the components of a system and processes within the system, 2. to identify relationships among the system's components, 3. to organize the systems components and processes within a framework of relationships, 4. to make generalizations, 5. to identify dynamic relationships within the system, 6. to understand the hidden dimensions of the system, 7. to understand the cyclic nature of systems 8. to think temporally (i.e. retrospection and prediction). Other theoretical foundations model the structure of system thinking in form of seven domains of system thinking skills, including the comprehension of elements, spatial and temporal boundaries, subsystems as well as relationships and developmental processes (Evagorou et al., 2009). Following a long tradition of cognitive development research in treating knowledge as differentiated into conceptual and procedural knowledge, Riess & Mischo (2010) accommodate Ossimitz' (2000) structural classification with declarative knowledge (for the first three dimensions) and procedural knowledge (for the fourth dimension), leaning towards the descriptions of Frensch & Funke (1995) and Leutner & Schrettenbrunner (1989). All these studies focusing on the characterization of system thinking theoretically based their hypotheses on different structural patterns mirroring the various facets of abilities and skills that are inevitable for system thinking. Moreover, these approaches share the assumption of a compartmented construct of system thinking, but there is disagreement concerning the number of structural dimensions (Fig. 3). Moreover, none of these references provides evidence for two or more empirically distinguishable dimensions of system thinking.



**Figure 3:** Overview of research findings and theoretical foundations for the dimensionality of system thinking's structure

With respect to German educational research this structural assignment can be attributed to the development of so called “competence models” that have been established within the framework of educational standards to specify certain skills and abilities students are expected to acquire (Klieme & Leutner, 2006).

### 2.3. Relation between System Competence and System Thinking

The introduction of educational standards in Germany has led to an increased focus on modeling of scientific competence (Schecker & Parchmann,

2006). Driven by a new formulated “learning outcome” orientation, competencies functioned as key objects that are required in a certain grade level (Köller & Parchmann, 2012) and thereby served as framework for common educational standards.

The concept of competence refers to Weinerts’ (1999) definition of “an individually or interindividually available collection of prerequisites for successful action in meaningful task domains”, encompassing cognitive abilities as well as motivational, ethical, volitional and social components (Weinert, 1999, p.5). Thus, competence, leading to a powerful communication of the individual with the environment (White, 1959) is considered as disposition in mastering problems of a certain type achieving a good performance with specific requirements (Klieme et. al., 2003). Additionally, for being susceptible in certain educational processes, competences can be separated from general cognitive abilities (Schecker & Parchmann, 2006). However, in the context of competence assessment, research usually focuses on the cognitive component of competence, defined as “context specific cognitive performance disposition, functionally referring to certain domain specific requirements” (Klieme & Leutner, 2006, p. 879).

Since the measuring of competences plays a central role concerning the optimizing of educational processes, there is need for concrete measurement opportunities to make certain competence levels visible. As a result, the development and application of competence models became a focal point of interest (Schecker & Parchmann, 2006). These models are able to characterize learning outcomes that are domain-specifically required at a certain grade level (Klieme et. al., 2003). In doing so, competence models describe the way of competence acquisition. Additionally, a differentiation between structural models and developmental models



on the one hand and normative and descriptive models on the other hand can be made. Developmental models illustrate particular levels of competence development, relating to chronological sequence development (Bernholt, Parchmann, & Commons, 2009). Structural models in contrast focus on the competence pattern without assuming developmental chronology. Normative models, serving as theoretical foundation, illustrate all cognitive requirements to cope with certain demands successfully. In contrast, descriptive models allow for concrete “typical” definition, based on empirical evidence (Schecker & Parchmann, 2006). Though being discussed critically, the introduction of such competence models not only allows for precise and comparable measuring of students’ performance but also for characterizing structure and development of competencies, their affiliation according to domains and other constructs as for example intelligence (Köller & Parchmann, 2012). However, many studies remain at the normative competence characterization. Thus, to serve a reliable framework in form of descriptive competence models, research is needed to verify the underlying normative models.

To address this lack of evidence this study aims at clarifying the structural pattern of system thinking. Therefore, this study theoretically leans against the study of Sommer and Lücken (2010). They derived a model of system competence, basically rooting in systems’ theoretical characteristic criteria. These criteria were subdivided into two dimensions “system organization” and “system properties”. Following this two-dimensional system structure Sommer & Lücken (2010) derived all necessary abilities and skills compassing system competence in a system oriented framework. As result, from a normative point of view, they investigated system competence as compassing a structural dimension (“system organization”) and a procedural dimension (“system properties”) (Tab. 2).

**Table 2:** System characteristics and abilities of system competence (Sommer & Lücken, 2010)

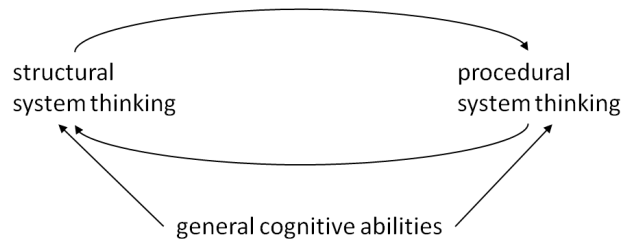
System characteristics		Abilities composing system competence	
System organisation	Structure of elements and their relationships	Modelling	<ul style="list-style-type: none"> <li>to identify system elements and to associate them with each other</li> <li>to organize system elements and their relationships in a reference framework</li> </ul>
	Identity		<ul style="list-style-type: none"> <li>to recognize and utilize system borders</li> </ul>
System properties	Emergence	Dealing with systems' properties	<ul style="list-style-type: none"> <li>to distinguish the attributes of the system from the attributes of the elements</li> </ul>
	Dynamics		<ul style="list-style-type: none"> <li>to identify dynamic relationships</li> <li>to predict the consequences of changes</li> </ul>
	Effects		<ul style="list-style-type: none"> <li>to assess the effects in a system</li> <li>to identify and describe reactions</li> </ul>

However, the distinction and interrelations between those postulated compartments of system thinking in this model dissociated with respect to the models mentioned above. Moreover, evaluations and assessment approaches differed in each design. Consequently, there is necessity for modeling and validation of the structure of system thinking empirically.

#### 2.4. Empirical foundation for the internal relations of System Thinking

Several studies account for a close relationship regarding the internal dimensions of system thinking (Verhoeff, Waarlo, & Boersma, 2008; Riess & Mischo, 2010; Sommer & Lücken, 2010). However, these assumptions have been made theoretically and little is known so far about the precise internal relations. With

respect to cognitive development research, recent findings provided empirical evidence supporting the iterative (bidirectional) model of knowledge development (Schneider, Rittle-Johnson & Star, 2011), with two kinds of knowledge accounting for each other reciprocally (Fig. 4).



**Figure 4:** Iterative model of system thinking development

This illustration of knowledge development with reciprocal impact might also be a plausible approach for the internal dimensions of system thinking. From a “bottom up” point of view, the structuring of new acquired systems’ content knowledge may support the understanding of system multilayered processes and feedback-loop thinking. On the other hand, experiencing systems’ behavior and processes might as a “top down” influence support the understanding of systems’ structure, elements and concept functioning.

Thus, the following questions result from these underlying assumptions:

1. Do the internal dimensions of system thinking have an impact on the development of each other?
2. Is the iterative model of knowledge development an appropriate approach to the internal structure of system thinking?

There is need for an empirical clarification of the internal structure of system thinking particularly with respect to the internal connections and dependencies.

## **2.5. Empirical foundations for the development of System Thinking in different ages**

Regarding the introduction and use of system thinking at school there is no agreement about the appropriate age. Recommending the implementation of system thinking as early as possible, several findings provide evidence for elementary school students being able to develop basic system thinking (e.g. Assaraf & Orion, 2010; Evagorou et al., 2009; Sommer & Lücken, 2010). Contrariwise, diverse authors argue that system thinking - as it is necessary to reconstruct complex systemic processes - implicates higher order thinking skills which are even challenging at university level (Frank, 2000; Jacobson and Wilensky, 2006). Natural systems pose immense difficulties on students', tending to simple causal and linear explanatory statements in the context of biology rather than towards the reconstruction of complex systemic processes (Hogan & Fisherkeller, 1996; Reiner & Eilam, 2001). Learning biology still results in expressing details and linear relations of phenomena, neglecting the macroscopic-level expression (Wilensky & Reismann, 2006). To overcome these challenges, Boersma et al. (2011) recommend the introduction of system thinking as early as in elementary school to prepare for understanding of cause-effect, form-function, and part-whole relationships corresponding to systems emergence in secondary school education. Still, there is deficient empirical fundament on the development of system thinking in different ages.

Consequently, there is need to focus not only on the existence of age-dependent differences but also on a precise definition concerning the internal structure pattern of system thinking in different ages. This in turn is closely tied in with

open questions concerning the influence of general cognitive abilities on system thinking. As Frank (2000) requires a higher level of cognitive abilities for adequate system thinking, it is of central interest if older students could benefit more efficiently from their “higher level” system understanding, than younger students do.

On the other hand, it might be conceivable that younger students’ system thinking development is primarily influenced by their structural understanding of complex systems, that possibly plays a bigger role regarding to the development of structural system thinking than to the development of procedural system thinking. Therefore, another question that addresses the internal relations of system thinking is: Are there differences concerning these relations between structural and procedural system thinking with respect to different grades? Additionally, it might be interesting, how general cognitive abilities contribute to both structural and procedural system thinking at each grade. Consequently, the aims of the fourth study were threefold: 1) To test for differences between 4<sup>th</sup> and 8<sup>th</sup> grade students concerning the general level of structural and procedural system thinking 2) to test whether the predictive relations between structural and procedural system thinking are bidirectional concerning both in 4<sup>th</sup> and 8<sup>th</sup> and 3) to evaluate how the internal structure pattern of system thinking in both grades contribute to general cognitive abilities.

## **2.6. Development of an appropriate biological system for system thinking assessment**

The awareness of ecosystem loss and the effects of structural changes within ecosystems have led to ongoing debates about new aims becoming apparent in the future (Norris, K. 2012; Rands et al. 2010). There is applied need for systems

approaches in the context of ecosystem loss and degradation. The habit of individuals, the way they act and interact within their environment generates effects that are spread out through ecosystems. Effects concerning their population arise as well as effect concerning the ecosystem their population is part of. As a consequence, the environment changes and this in turn affects populations, communities, individuals and the wider ecosystem. These arguments form the basis for a systems approach to ecosystems and biodiversity change (Loreau, 2010). Consequently, the prospective potential of systems approaches may have great advances concerning the future change of environmental conditions that have been mostly analyzed retrospectively, yet. This potential will be of relevance particularly with respect to educational settings, where the ability to predict, a systems future behavior, is a central fact of any science (Evans, Norris, Benton, 2012). Regarding to biology curricula, focusing on separated aspects and detailed knowledge is popular rather than acquiring a holistic approach (Boersma, et al., 2011). Owing to pragmatic reasons, biological themes are sub-divided into different subjects, worked out in different disciplines like ecology, genetics, cell biology, evolutionary biology. This separation hinders the understanding of relations and connections between biological subjects (Verhoeff, 2003). Moreover, “students will fail to acquire an integrated picture of life phenomena” (Verhoeff, 2003, p. 44). This lack of systems understanding continues throughout further education and leads to considerably failure in system thinking even at university age (Jacobson & Wilensky, 2006).

Therefore, there is explicit need for the development of suitable teaching units that offer different perspectives on living systems and introduce a meaningful concept of systems into education. An ecosystem approach offers a multilevel approach including the levels of structure and processes. The integration of the essential

content knowledge into a coherent understanding of an ecosystem should provide an appropriate basis to introduce and facilitate system thinking. Providing suitable system approaches will bring benefits not only to the holistic understanding of ecosystems in the natural world but also to facilitate predictive ecology.

### **3. Aims of the studies**

The following chapter compasses the description of the aims of the studies conducted, the underlying definition of system thinking and the subsequently emerging aims and research questions of each study.

#### **3.1. The overall aim of the studies and underlying description of system thinking**

Since there is an immense demand concerning the implementation of complex system principles to foster an adequate scientific understanding, science education research emphasizes the important role of system thinking in educational contexts. System thinking requires a wide amount of cognitive abilities and therefore poses immense difficulties to students of different school age. However, system thinking is still not an explicit part of science education standards in Germany.

Therefore, this study investigated an empirical framework for system thinking characterization, compassing the development of an appropriate and comprehensive biological system intervention unit, suitable assessment practices and the validity of the theoretical construct structure. Additionally, investigating the construct of system thinking in these studies contributes to current topics in the field of system thinking research like relations to general cognitive abilities and age dependency.

### 3.2. Definition of system thinking and theoretical model reference

System thinking is defined here as an ability to understand the multilevel structure of systems' essential elements, their hierarchical and dynamic relationships, compassing the structural organization as well as the procedural developmental processes of complex systems.

The implementation of system thinking in the studies presented here is based on a theoretical characterization of system thinking in form of two dimensions "structure" and "function" (Fig.3) that are recurring through literature since the first "roots" of system thinking. Referring to the actual investigations on system thinking, based on model of system competence (Sommer & Lücken, 2010), implies the distinction between two underlying dimensions "system organization" and "system properties", each compassing a definite set of abilities. System organization in this dissertation is referred to as structural system thinking and system properties here is referred to as procedural system thinking:

Dimension 1:        ***structural system thinking***

(compassing the understanding of the hierarchical structure of elements, their relationships and identity)

Dimension 2:        ***procedural system thinking***

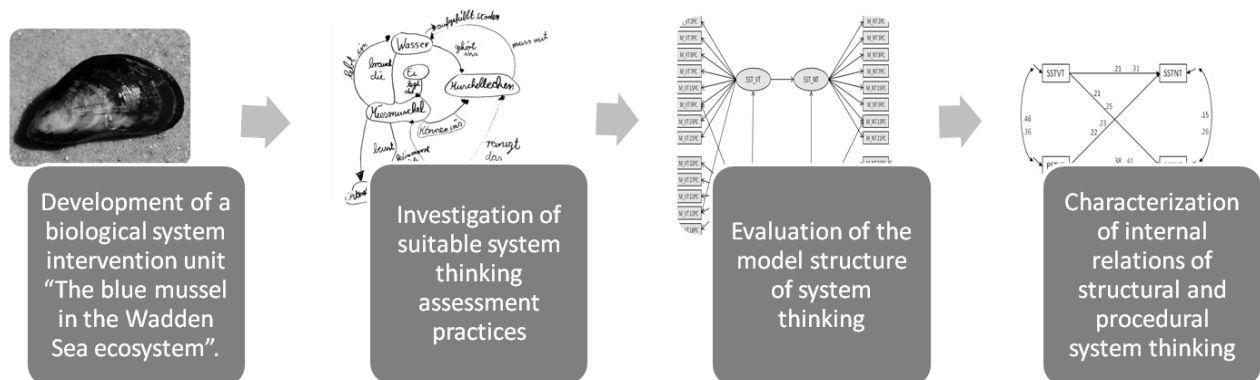
(compassing the understanding of systems' emergence, dynamic and nonlinear feedback loop interactions and developmental processes of a system)



The methodological approach of the studies presented here was realized on the basis of an intervention unit, compassing the development system oriented approach to a biological ecosystem “The blue mussel in the context of the Wadden Sea ecosystem”. This system oriented approach served as content reference for the development of the assessment instruments, evaluated in the first study and for the model based structural validation in the second and third study. The theoretical model of system thinking served as framework for validation in study two and three.

#### 4. Overview on the study procedure

To support an empirical fundament for system thinking characterization, this thesis compasses the development of a biological ecosystem intervention unit, investigation of suitable assessment practices, the modeling and analysis of the construct structure (Fig. 5).



**Figure 5:** Overview on the study procedure

##### 4.1. Development of a biological system intervention unit

The first step to aim for providing a system oriented approach for investigating system thinking was the development of an ecosystem unit.

The blue mussel (*Mytilus edulis*) in the context of the Wadden Sea ecosystem offers an appropriate multilevel system, involving concepts from the mussel as organism to ecological perspectives relating to the water preserving filtration, associated feeding relations or the providing of space for over a hundred species, living on or between them. Moreover, blue mussel beds are of great importance concerning the Wadden Sea ecosystem, serving as diverse habitat and as fundamental food source for a number of species, especially mussel-eating birds (Nehls et al., 2009). The development of mussel beds is strongly influenced by factors like fisheries but also by natural factors like climate change. The spatfall for example depends on winter temperatures – decreasing winter temperatures are required to increase spatfall. Consequently, the availability of seed mussels is closely related to the temperature in January – March (Dankers & Zuidema, 1995; Strasser & Günther, 2001a; Beukema & Dekker, 2005). Moreover, apart from abiotic factors, there are certain biotic factors blue mussels have to cope with, like natural predators or bio-invaders as the Pacific oyster (*Crassostrea gigas*). Since being a suspension feeding organism, the Pacific oyster is competing with blue mussels, while having higher filtration rates and no natural predators in the Wadden Sea (May, 2006). This potential risk is an important aspect regarding to the blue mussel ecosystems' developmental processes. However, while enhancing the ecological function of the Wadden Sea by promoting diverse communities, the blue mussel serves as a suitable example for a system based teaching unit. Therefore, the assessment of system thinking in this study is based on a blue mussel intervention unit (Table 3).

**Table 3:** Overview about the intervention unit “The Blue Mussel in the context of the Wadden Sea ecosystem”

<b>Introduction</b>	<i>„What kind of animals are blue mussels? “</i>
<b>Respiration and Feeding Habitat</b>	<i>„One of the most astounding forms of life! “</i>
<b>Way of Life</b>	<i>„How to cope with low tides at intertidal flats? “</i>
<b>Development and Reproduction</b>	<i>„ Are blue mussels able to provide for effective spatfall? “</i>
<b>Predators</b>	<i>„How do blue mussels defend their self against predators? “</i>
<b>Breeding and Fishery</b>	<i>„The most dangerous enemy, known as: human! “</i>

#### **4.2. Research questions of investigations on system thinking concerning assessment and structural validation**

The following investigations were conducted to develop appropriate system thinking assessment tools, especially with regard to large-scale assessment. In particular, differences between traditionally used paper-pencil- and computer based-practices are evaluated, while additionally focusing on adaptability at elementary and secondary school. Beyond that, differences between one-factor and two-factor model structures of system thinking are investigated to provide empirical evidence for measurement invariance concerning structure model validation. A control group without getting the intervention unit served as reference value. Due to the internal structure pattern of system thinking, the relationships between structural and procedural system thinking are investigated and related to the influence of general

cognitive abilities. Again, all investigations concerning the structural evaluation differentiate between elementary and secondary school students' level of system thinking and system thinking development.

#### **4.2.1. Aims of study 1**

Though Concept Mapping has been suggested as suitable assessment tool for system thinking, there is only poor evidence concerning the effect of particular Concept Mapping features on a valid assessment of system thinking. Therefore, this study aims at the investigation of different Concept Mapping practices with respect to the comparison of computer and paper-pencil based practices on the one hand and the comparison of highly and nondirected practices on the other hand. These features were evaluated with respect to their influence on students' Concept Mapping performance and the validity of different Concept Mapping practices for system thinking. Additionally, a comparison between fourth and eighth graders allows for suggestions concerning the application possibilities at elementary and secondary school.

The following research questions were developed:

1. Does the medium (computer vs. paper-pencil) and/or the directedness (highly vs. nondirected) influence students' performance in Concept Mapping?
2. Does the medium (computer vs. paper-pencil) and/or the directedness (highly vs. nondirected) influence the validity of students' Concept Mapping regarding procedural and structural system thinking?

#### **4.2.2. Aims of study 2: Evaluation of the model structure of system thinking**

Study 2 ties in with study 1 aims to provide empirical evidence for the structural pattern of system thinking, particularly with respect to the comparison of elementary and secondary school. Owing to the requirement of diverse cognitive abilities, previous interpretations of the internal structure of system thinking differ substantially concerning the number of latent variables. By bridging this gap of empirical evidence, this study seeks to characterize the behavior of system thinking's structure in a longitudinal view. Thus, a measurement invariance analysis is conducted to collect evidence about the construct validity concerning factorial invariance across two measurement points and across two different grades.

The research questions of the current study were the following:

1. Is there any evidence for a two-dimensional structure model of system thinking predominating a one-factor model regarding the comparison between elementary and secondary school?
2. Is there any evidence for measurement invariance regarding the two-factorial model of system thinking?
3. Is the two-factorial model of system thinking invariant across different grades?

#### **4.2.3. Aims of study 3: Characterization of internal relations of structural and procedural system thinking**

Following structural implications from study 2, study 3 aims at the characterization of internal relationships between structural and procedural system thinking. Though being characterized as two factorial construct, the investigation of system thinking in study 1 and 2 revealed a close connection in form of a high correlation between structural and procedural system thinking. Thus, questions arose concerning the development of each aspect of system thinking. A "bottom up"

development regarding the structuring of new acquired systems' content knowledge leading into a procedural system understanding might be conceivable as well as a "top down" influence of understanding system related processes supporting the understanding of systems' structure, elements and concept functioning. Moreover, the influence of general cognitive abilities is of particular interest in this case. Suggesting older students to revert to a higher level of cognitive abilities might be closely connected to an adequate understanding of systems' macroscopic behavior. In doing so, older students can be suggested to profit from their procedural system thinking more efficiently concerning the understanding of both microscopic and macroscopic level. According to elementary students, developing system thinking is possibly influenced by their structural understanding of complex systems potentially playing a more important role concerning the development of structural system thinking instead of procedural system thinking's development.

Therefore, the following questions continue to clarify the structural characterization of system thinking:

- 1) Which general level of structural and procedural system thinking do elementary students achieve in comparison to secondary students?
- 2) Is there evidence for a bidirectional relationship between structural and procedural system thinking both in 4<sup>th</sup> and 8<sup>th</sup> grade?
- 3) How does the internal structure pattern of system thinking contribute to general cognitive abilities both in 4<sup>th</sup> and 8<sup>th</sup> grade?

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**DEVELOPMENT OF AN INTERVENTION UNIT**  
**“THE BLUE MUSSEL IN THE CONTEXT OF THE WADDEN**  
**SEA ECOSYSTEM”**

Brandstädter, K., (2010). Hier steckt Leben drin:  
die Miesmuschelbank als System. *Unterricht Biologie*, 360, 10-16.

## **Hier steckt Leben drin: die Miesmuschelbank als System**

Die blauschwarzen Teppiche aus Miesmuscheln, die den Wattboden überziehen, bergen artenreiche Wohngemeinschaften. Funktion und Überleben dieser Systeme hängt vom Zusammenspiel seiner Elemente ab: Jede einzelne Miesmuschel filtert als «Mini-Kläranlage» pro Stunde etwa zwei Liter Meerwasser und nimmt dabei außer Sauerstoff und Nahrung auch unverdauliche Schwebeteilchen auf. Wieder ausgestoßen lagern sich diese Partikel als Schlick ab und heben die Muschelbank mit ihren zahlreichen Bewohnern allmählich an. Unter Wasser stellen Eiderenten, Seesterne und Krebse den Miesmuscheln nach, über Wasser fischen Möwen, Austernfischer und der Mensch nach den eiweißhaltigen Weichtieren.

Sie ist relativ unscheinbar, lebt an nahezu allen Küsten mit geeignetem festen Untergrund und spielt eine zentrale Rolle im Ökosystem Wattenmeer: die Miesmuschel (*Mytilus edulis*). Die Weibchen geben im Frühjahr 5 bis 10 Millionen Eier ins Wasser ab, wo sie durch die Samenzellen der männlichen Muscheln in der Umgebung befruchtet werden. Aus den befruchteten Eizellen entwickeln sich zunächst Trochophora-, später Veliger-Larven, die mit dem Plankton verdriftet werden. Ein Bruchteil überlebt und entwickelt sich zu Jungmuscheln, die sich bevorzugt in der Nähe anderer Muscheln festsetzen (Borcherding 2001).

## **Die Miesmuschelbank als Lebensversicherung**

Die Miesmuschel gehört zu den wenigen Zweischalern (Bivalvia), die die wechselhaften Bedingungen im Wattenmeer aushalten: Zweimal pro Tag fehlt das lebenswichtige Wasser, mitunter brennt die Sonne ziemlich heiß, es friert im Winter,

und ab und zu stürmt es heftig. Im Gegensatz zu anderen heimischen Muscheln lebt die Miesmuschel oberirdisch, sie kann sich den extremen Umweltbedingungen weder durch Flucht noch durch Eingraben entziehen. Erfolgsrezept der Miesmuschel sind die proteinhaltigen Byssusfäden (Abb.1), die sie mit einer Drüse an ihrem Fuß produziert, wie Moos aussehen und der Miesmuschel ihren Namen gaben (mhd. mies = Moos).



**Abbildung 1:** Miesmuschel mit Byssusfäden (Foto: M. Zinkova)

Diese extrem strapazierfähige, wasserfeste und dehnbare «Muschelseide» dient inzwischen als Vorbild für technische Anwendungen. Indem sich Miesmuscheln mit den Byssusfäden aneinander heften, entstehen quadratkilometergroße Muschelbänke (Abb. 2), die zahlreichen «Untermietern» Lebensraum bieten, z. B. Algen, Krebsen, Schnecken, Würmer, Garnelen und Jungfischen (Kock,1998). Durch die hohe Artendichte zählen Miesmuschelbänke zu den produktivsten Biotopen in der vergleichsweise artenarmen Umgebung. Eine Miesmuschelbank stellt ein komplexes



dynamisches und lebendiges System dar, dessen Elemente auf funktionaler und struktureller Ebene in charakteristischer Wechselbeziehung stehen.



**Abbildung 2:** Muschelbank (Foto: G. Millat)

### **Fressen und Gefressen werden**

Miesmuscheln gehören zu den Filtrierern, d. h. sie ernähren sich von Plankton. Das Wasser gelangt über die Einströmöffnung in die innere Mantelhöhle der Muschel. Dort umspült es den Kiemenkorb. Über die Kiemenlamellen nimmt die Miesmuschel Sauerstoff auf, der über ein offenes Kreislaufsystem zum Herzen gelangt. Außerdem bleiben an den Lamellen verdauliche Partikel hängen, die über eine Rinne in Richtung Mund gestrudelt werden (Gruner, Hannemann, & Hartwich, 1993). Unverdauliche Reste werden als «Scheinkot» ausgeschieden. Der sich ansammelnde Schlack zwingt die Muschel, sich immer wieder mithilfe der Byssusfäden klimmzugartig an den Artgenossen nach oben zu ziehen. Dadurch wachsen die Muschelbänke langsam in die Höhe. Der lateinische Arname «edulis»

besagt, dass Miesmuscheln essbar sind. Sie stehen beispielsweise auf den Speiseplänen von Seesternen, Wellhornschnecken, Strandkrabben, Möwen, Austernfischer und Eiderenten, die teils über, teils unter Wasser auf Muscheljagd gehen. Auch der Mensch fischt, züchtet und verzehrt jährlich viele Tausend Tonnen Muschelfleisch. Problematisch hierbei ist, dass die Muscheln vielfach mit Schadstoffen belastet sind, die sie mit dem Wasser einstrudeln. Besonders häufig werden hohe Konzentrationen von Schwermetallen wie Quecksilber, Blei und Cadmium sowie das hochgiftige Tributylzinn (TBT) nachgewiesen, das Schiffsrümpfe frei von Bewuchs halten soll. Mitte der 1960iger Jahren waren die wilden Muschelbänke zu großen Teilen abgefischt und zerstört. Die damals eingeführte pazifische Auster (*Crassostrea gigas*) beansprucht den gleichen Lebensraum und die gleiche Nahrung wie die Miesmuschel. Allerdings wächst ihr schneller eine viel dickere Schale – die natürlichen Feinde der Miesmuschel können ihr deshalb nichts anhaben. Daher überwachsen die Austern vielfach die Miesmuschelbänke und verdrängen die ursprünglichen Bewohner (Nehls, Witte, Buttger, Dankers, Jansen, Millat, Herlyn, Markert, Sand Kristensen, Ruth, Buschbaum, & Wehrmann, 2009). Miesmuscheln für den Verzehr werden – oft an hängenden Leinen – auf Flächen kultiviert, die nie trocken fallen. Das verringert den Stress durch wechselnde Umweltbedingungen und den Feinddruck, sodass die Muscheln schneller wachsen. Die jungen «Saatmuscheln» werden in der Regel aus dem Ausland eingeführt. Die Begleitfauna, vor allem Fressfeinde wie z. B. Seesterne, werden regelmäßig abgefischt. Daher sind Muschelkulturen artenärmer als natürliche Muschelbänke. Spätestens bei der Ernte der Muscheln werden dort siedelnde Organismen getötet; zumindest verlieren sie ihren Lebensraum. Naturschützer kritisieren auch den Flächenbedarf der Muschelkulturen: Allein im Nationalpark Schleswig-Holsteinisches

Wattenmeer, wo keine natürlichen Muschelvorkommen mehr ausgebeutet werden dürfen, werden auf 2000 ha Kulturmuscheln gezüchtet. Durch die Schlickbewegungen bei der Muschelernte werden zudem vermehrt Mineralstoffe freigesetzt, die Algenblüten begünstigen.

### **Bemerkungen zum Unterricht**

Schulen in Küstennähe sollten die Möglichkeit nutzen, auf einer Wattwanderung Muschelbänke direkt in Augenschein zu nehmen. Führungen bieten z. B. die Schutzstation Wattenmeer, der NABU und andere ortsansässige Naturschutzverbände an (Termine im Internet). Lebende Miesmuscheln sind an den Küsten von Nord- und Ostsee, an Stegen oder Hafenanlagen sehr leicht zu sammeln. Pfahlkratzer (im Internet zu bestellen, ab 45,- €) erleichtern das Abkratzen; ein ausrangierter Apfelpflücker erfüllt den gleichen Zweck. Binnenländer können fangfrische Miesmuscheln im Fischhandel erwerben und im Aquarium halten (► Kasten 1). So lassen sich Details wie die Ein- bzw. Ausströmöffnung und der Fuß mit der Byssusdrüse genauer studieren. Mit etwas Geduld kann man, vor allem bei jungen Muscheln, auch das Anheften der Byssusfäden beobachten und deren Reißfestigkeit testen. Im Unterricht wird die Komplexität der betrachteten Systeme schrittweise erweitert: Nach der einzelnen Miesmuschel als «Mini-Kläranlage» wird das übergeordnete System «Muschelbank» in den Blick genommen: der Einfluss abiotischer Faktoren im Lebensraum und die Vernetzung mit Artgenossen, «Untermietern» und Räubern. Die Auseinandersetzung mit Naturschutzaspekten und den wirtschaftlichen Interessen der Muschelfischerei stellt wiederum das System «Muschelbank» in den größeren Kontext des Ökosystems Wattenmeer. Spielerische Rollen- und Perspektivwechsel erweitern die Bewertungskompetenz der

SchülerInnen. Die Antizipation möglicher Folgen von Veränderungen fördert ein ganzheitliches Systemverständnis.

## **Das lebende Tier hinter der «toten» Schale**

### 1. Unterrichtsabschnitt

Zum Einstieg werden einzelne Muscheln oder kleinerer Muschelklumpen in Bechergläsern (ca. 500 ml) präsentiert. Die Überraschung ist groß, wenn ein scheinbar «lebloses » Tier nach einigen Minuten aktiv wird, die Schalen öffnet und sich bewegt. Voraussetzung ist Ruhe rund um die Tische. Sichtbar werden die vom Mantelrand umrahmte Einströmöffnung und darüber die Ausströmöffnung. Häufig strecken Miesmuscheln ihren Fuß heraus, an dessen Spitze sich die Byssusdrüse befindet. Die SchülerInnen tauschen ihre Vorkenntnisse über die Lebens- und Ernährungsweise von Muscheln aus. Zur Demonstration der enormen Filterleistung werden zwei große Bechergläser (0,75 l) mit Schlickwasser gefüllt. Alternativ werden pro Glas ein Esslöffel Tonerde (Apotheke oder Drogerie) und ein halber Teelöffel Algenpulver (Zoohandel) in Wasser gelöst. In ein Glas werden 10 mittelgroße Muscheln gesetzt, das andere bleibt muschelfrei. Im Laufe einer Unterrichtsstunde wird das Muschelbecken klar, das Kontrollbecken bleibt trüb. Währenddessen machen die SchülerInnen in Gruppenarbeit den Wasserstrom sichtbar, der den Körper der Muscheln unablässig durchströmt und sie mit Sauerstoff und Nahrung versorgt (► Material 1). Der Farbstoff Uranin (Apotheke) ist ungiftig und wird bei der Kontrolle von undichten Wasserleitungen eingesetzt. Alternativ kann Lebensmittelfarbe oder Karminrot verwendet werden. Etwa 5 bis 10 Minuten, nachdem die Farbe eingestrudelt wurde, wird am Hinterende farbiger Scheinkot ausgeschieden. An einer geöffneten Muschel kann mithilfe eines Binokulars der «Transportweg» im Körper

verfolgt werden (► Kasten 2). Wer vor den Augen der SchülerInnen keine Muschel opfern möchte, kann den Versuch im Internet ansehen lassen (Film zur Kiemenaktivität unter [www.uni-duesseldorf.de/Math-Nat/Biologie/Didaktik/Wattenmeer/4\\_tiere/dateien/miesmuschel.html](http://www.uni-duesseldorf.de/Math-Nat/Biologie/Didaktik/Wattenmeer/4_tiere/dateien/miesmuschel.html)).

## **Ein schwieriger Lebensraum**

### 2. Unterrichtsabschnitt

Bilder vom Gezeitenwechsel im Wattenmeer, Sturmfluten, Landunter auf den Halligen, Eisschollen im Watt oder wattwandernden Touristen an heißen Sommertagen demonstriert die wechselhaften Bedingungen im Watt (Bilder liefert z. B. das Projekt «Wandel im Watt» ► [www.wattenmeer-nationalpark.de/wandel-im-watt/html/frameset.htm](http://www.wattenmeer-nationalpark.de/wandel-im-watt/html/frameset.htm)). In zwei arbeitsteiligen Gruppen erarbeiten die SchülerInnen (► Material 2: A Byssusfäden und Muschelbänke; B Gezeiten und Temperatur), wie Miesmuscheln den abiotischen und biotischen Umweltfaktoren in ihrem Lebensraum standhalten. Anschließend tauschen sie ihr Wissen in einem «Expertenkongress» mit ihren Nachbarn aus und beantworten schließlich gemeinsam Fragen zum Thema.

## **Die Miesmuschel im Nahrungsnetz**

### 3. Unterrichtsabschnitt

Um die Rolle der Miesmuschel im Nahrungsnetz des Wattenmeers zu verdeutlichen, erhalten die SchülerInnen zunächst kurze Steckbriefe der beteiligten Tierarten (► Material 3). Anschließend werden Rätsel verteilt oder vorgelesen, die diese Tierarten charakterisieren. Jede richtig erratene Art wird mit Punkten belohnt. Alternativ können die SchülerInnen sich selbst kleine Rätselfragen ausdenken. An

der Tafel oder als Hausaufgabe wird ein Nahrungsnetz entwickelt, in dessen Mittelpunkt die Miesmuschel steht.

## **Miesmuscheln auf unserem Speiseplan**

### 4. Unterrichtsabschnitt

Miesmuscheln werden auch von Menschen gerne gegessen. Verbraucher, Muschelfischer und Naturschützer beurteilen die Muschelfischerei unterschiedlich. Für ein Rollenspiel erarbeiten die SchülerInnen die jeweiligen Argumente (► Material 4). Ziel der folgenden Diskussion ist nicht unbedingt eine endgültige Lösung. Wichtig ist, dass alle Gruppen eine gewisse Kompromissbereitschaft zeigen. Die vielschichtigen Vernetzungen rund um die Miesmuschel können abschließend in Form einer concept map, als Tafelbild oder Wandposter gemeinsam zusammengefasst werden.

### **Material 1**

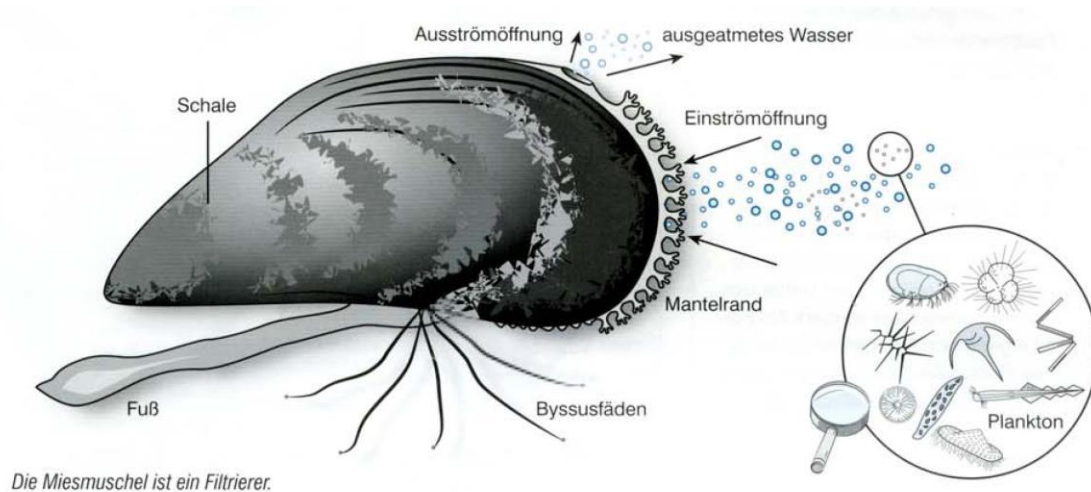
#### **Wie ernähren sich Miesmuscheln?**

**Material pro Tisch:** 1 Becherglas (500 ml) mit rund 300 ml Salzwasser; 1 Miesmuschel, 1 Pipette, Uraninlösung (1 Messerspitze Uraninpulver in 200 ml Salzwasser)

#### **Aufgaben**

- Beobachtet mehrere Minuten in Ruhe, ob sich die Muschel verändert, bewegt, öffnet ...
- Gebt mit der Pipette vorsichtig (!) einige Tropfen Uraninlösung in die Nähe der Einströmöffnung und beobachtet von oben, was mit der Farbe geschieht.

- Beschriftet die Abbildung mit Schale, Fuß, Byssusfäden, Mantelrand, Einströmöffnung, Ausströmöffnung und kennzeichnet den Ein- und Ausstrom des Wassers mit Pfeilen.



**Abbildung 3:** Die Miesmuschel ist ein Filtrierer.

## Material 2

### Überleben im Watt

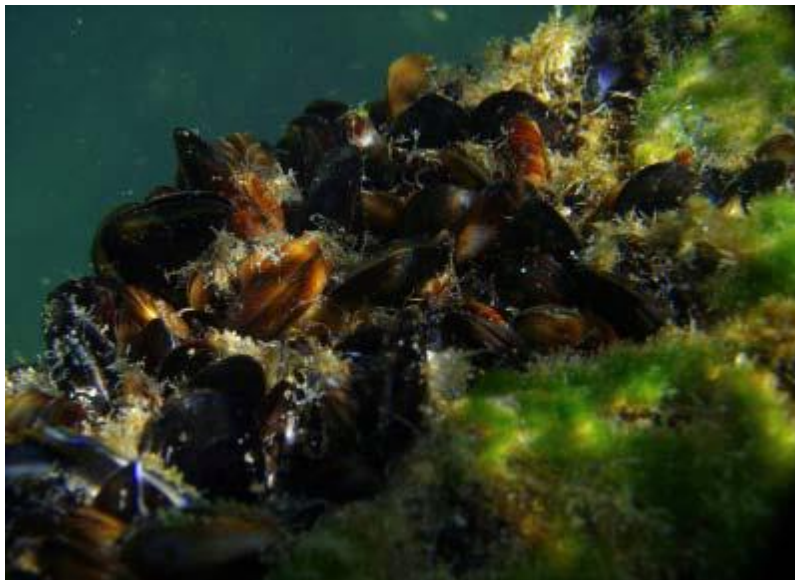
Mal peitschen stürmische Winde über das Watt, mal hohe Wellen. Nichts bietet Schutz vor Hitze und Eiseskälte. Miesmuscheln halten diesen Bedingungen stand.

### Aufgabe

- Bildet Zweier-Expertenteams: Experte A beschäftigt sich mit der Miesmuschel und den Muschelbänken, Experte B informiert sich über Temperaturen im Watt und die Gezeiten. Anschließend informiert jeder Experte seinen Nachbarn über sein Thema. Danach beantwortet das Team gemeinsam die unten stehenden Fragen.

## A1 Die Sicherheitsleinen der Miesmuschel

Vom lebenden Tier ist bei einer Miesmuschel wenig zu sehen. Manchmal streckt die Muschel ihren kräftigen Fuß heraus. An seiner Spitze sitzt die Byssusdrüse. Sie produziert extrem reißfeste Eiweißfäden. Eine Miesmuschel kann sich nicht wie andere Muscheln eingraben. Ist die Muschel mit den Byssusfäden an einen harten Untergrund oder an andere Muscheln angeheftet, kann die Strömung sie nicht mit sich reißen. Droht eine Miesmuschel durch Schlick und Sand verschüttet zu werden, kann sie sich mithilfe der Byssusfäden klimmzugartig nach oben ziehen.



**Abbildung 4:** Fest verzurrt: die Byssusfäden der Miesmuscheln (Foto: D. Laszlo)

## A2 Die Muschelbank als Lebensversicherung

Miesmuscheln leben zu Tausenden in Muschelbänken, die sich oft kilometerweit im Flachwasserbereich vor den Meeresküsten. Sie sind Lebensraum für zahlreiche «Untermieter»-Arten wie Garnelen, Würmer, Schnecken, Seepocken, Algen, Jungfische und natürlich auch für den eigenen Nachwuchs der Muscheln. Die festen Muschelschalen bieten Schutz vor Wind und Wellen, Sonne und Trockenheit.



Räuberische Tiere finden in den Muschelbänken reichlich Nahrung, Algen und Seepocken einen harten Untergrund inmitten unbeständiger Sandflächen. Miesmuschelbänke beherbergen 10 x so viele Organismen wie die übrigen Wattflächen und zählen damit zu den produktivsten Biotopen!

### **B1 Extreme Temperatur**

Im Wattenmeer herrschen extreme Temperaturschwankungen. Bei Ebbe heizt sich die Wattoberfläche auf bis zu 35 °C auf, um sich dann bei Flut um etwa 15 °C wieder abzukühlen – und das zwei Mal pro Tag! Im Winter sinken die Temperaturen bis auf – 5 °C. Wenn die Wattflächen vereisen, erfrieren viele Tiere, mitunter Millionen von Muscheln. Aber danach gibt es nicht nur weniger Muscheln, sondern auch weniger hungrige Krebse, die die Muschellarven fressen – Eiswinter zerstören also nicht nur Leben, sondern erhalten es auch.

### **B2 Gezeiten**

An der Nordseeküste bringt jede Flut für etwa sechs Stunden nähr- und sauerstoffreiches Wasser, sechs Stunden danach herrschen Trockenheit und Nahrungsmangel. Miesmuscheln überleben die lebensfeindlichen Bedingungen, indem sie ihre Schalen schließen, etwas Wasser darin zurückbehalten und ihre Stoffwechselprozesse stark drosseln. So verschlafen sie die Zwangspause.



**Abbildung 5:** Trockengefallene Miesmuschelbänke im Wattenmeer (Foto: J. v. d. Koppel)

► Für Menschen sind Ebbe und Flut, die ständigen Wechsel zwischen Hoch- und Niedrigwasser spannend zu beobachten. Für die Tiere im Wattenmeer bedeutet es puren Stress. Erklärt, warum vor allem die Ebbe für eine Miesmuschel mit Stress verbunden ist, und beschreibt ihre Überlebensstrategie.

► Erläutert, wieso Muschelbänke für die einzelne Muschel überlebenswichtig sind.

Wem nützen die Muschelbänke noch?

► Eiswinter können zu starken Einbrüchen in der Muschelpopulation führen. Stellt dar, welchen positiven Effekt solche Kälteperioden für die Muscheln haben.

### **Material 3**

#### **Auch Miesmuscheln haben Feinde**

**Die Allesfresserin:** Auf dem Speiseplan der **Silbermöwe** stehen Meerestiere, aber auch Speisereste und Fischabfälle sind willkommen. Muscheln schluckt sie ganz

herunter und zerdrückt sie im kräftigen Kaumagen. Die Schale wird als «Speiballen» ausgespuckt. Trotzdem ist sie den Muscheln nützlich, denn sie frisst bei Ebbe Seesterne – den Unterwasser-Todfeind der Miesmuscheln – von den Muschelbänken.



**Abbildung 6:** Speiballen einer Silbermöwe (Fotos: K. Brandstätter/D. Daniels)

**Die Große:** Die Eiderente ist die größte Ente an Nord- und Ostsee. Sie verbringt ihr Leben fast vollständig auf dem Meer. Lediglich für ihre Brut baut sie Nester auf dem Land. Die Daunen, auf denen sie den Nachwuchs weich bettet, schätzt auch der Mensch als Kissenfüllung. Hauptnahrung der Eiderenten sind Miesmuscheln, die sie bei Flut tauchend erbeuten und ganz herunterschlucken. Die Schalenreste spucken sie als «Speiballen» aus. Die Kraftanstrengung für das Tauchen lohnt sich erst ab einer Schalenlänge von 4 cm.



**Abbildung 7:** Eiderenten: das Männchen ist auffällig schwarz-weiß gefärbt, das Weibchen in unauffälligen Brauntönen gekleidet (Foto: K. Marshall)

**Der Lautstarke:** Ob Futtersuche oder Revierverteidigung – beim **Austernfischer** ist alles mit lautstarkem Geschrei verbunden. Wegen seines schwarzweißen Gefieders, den roten Beinen und dem roten Schnabel heißt er auch «Ostfriesen-» oder «Hallig-Storch». Je nach Lieblingsnahrung und Beschaffungstechnik, die die Jungvögel von ihren Eltern abgucken, unterscheiden sich die Schnabelformen: Nach Würmern stochert der spitze «Pfriemschnabel», der stumpfe «Hammerschnabel» hackt Muscheln auf, und der kurze kräftige «Meißelschnabel » öffnet die Schließmuskeln der Muscheln. Die Nahrungssuche findet nur bei Ebbe statt.

**Der Ausdauernde:** Seine Attacken kommen nicht überraschend. Der **Seestern** umschließt die Muschel mit seinen Armen und zieht oft mehrere Stunden an ihren Schalen. Die Muschel ermüdet allmählich, es sei denn, die Ebbe zwingt ihren Feind zum Rückzug. Hat der Seestern die Schließmuskeln überwunden, so stülpt er seinen Magen in die Muschel, zersetzt das Fleisch und schlürft den vorverdauten Brei auf.

**Die Knackige:** Sowohl als Räuber als auch als Futter spielt die **Strandkrabbe** eine wichtige Rolle im Ökosystem Wattenmeer. Sie ist ein Allesfresser. Ausgewachsene Miesmuscheln sind häufig zu hart für ihre Scheren, sie knackt daher bevorzugt die jüngeren Exemplare.

**Die Konkurrentin:** Die **Pazifische Auster** frisst keine Miesmuscheln, aber sie beansprucht den gleichen Lebensraum und bevorzugt die gleiche Nahrung. Außerdem ist ihre Schale robuster, sie wächst schneller und verdrängt die Miesmuscheln von ihren Bänken, indem sie einfach darüber wächst.

### **Wer bin ich?**

1. Ich muss manchmal tief tauchen, um an mein Lieblingsessen, die Miesmuscheln, heranzukommen. Zu kleine Bissen lohnen sich daher für mich nicht, und ich verschlucke jede Muschel samt Schale. *Eiderente*

2. Miesmuscheln sind lecker, aber Abfallkörbe lassen sich leichter leeren. Ein weggeworfenes Fischbrötchen schmeckt auch, und ich muss danach keine Schalen hochwürgen und ausspucken. *Silbermöwe*

3. In der Ruhe liegt die Kraft! Mit ein bisschen Ausdauer kommt das Muschelfleisch in meinem Magen und die leeren Schalen bleiben liegen. *Seestern*

4. Ich warte mit der Nahrungssuche auf die Ebbe. Mit dem Schnabel als Werkzeug komme ich nicht nur an Muschelfleisch heran, sondern stochere auch nach Würmern. *Austernfischer*

5. Ich kann mir meine Nahrung unter Wasser oder an Land besorgen. Muschelbänke bieten mir Nahrung und geeigneten Wohnraum, und der ist knapp im Wattenmeer. *Strandkrabbe*

## Material 4

### Muschelfischerei und Naturschutz

Bis in die 1990er Jahre hinein unterlag die Miesmuschel- Fischerei im Wattenmeer keinerlei Einschränkungen. Die Muschelfischer ernteten die Muscheln mit den bis heute gebräuchlichen Dredgen – Netzen mit einem Stahlbügel, der Muscheln bis zu 20 cm tief in den Boden hinein abschabt. Übrig bleibt nur der Sandboden, der den Muschellarven keine sichere Unterlage zur Ansiedlung bietet. Zwar fielen kleine junge Miesmuscheln durch die Netze der Fischer, aber ohne die großen Muschelbänke, die Wind und Wellen trotzen, kann der Muschelnachwuchs nur schwer überleben (Piersma, Koolhaas, Dekinga, Beukema, Dekker, & Essink, 2001). Irgendwann waren über 60 % der Miesmuschelbänke verschwunden – ein Drama für die Eiderenten (Buschbaum, & Nehls, 2003; Piersma, & Camphuysen, 2001).). Die großen Meeresenten ziehen im Herbst von Skandinavien ins Wattenmeer, wo sie sich mausern und Fettreserven für den Winter anfressen. Im Januar 2000 zählte man rund 30.000 Enten weniger als Mitte der 1990er-Jahre. Ähnliche Entwicklungen sind bei anderen Vogelarten zu befürchten, die bei ihren Wanderungen im Wattenmeer rasten und in den Muschelbänken nach Nahrung suchen. Inzwischen hat man vor den Küsten Muschelkulturen angelegt, um den Bedarf an Muscheln zu decken. Allein in Schleswig-Holstein werden pro Jahr rund 15.000 t Muscheln geerntet. Die «Saatmuscheln» stammen von Wildbänken. Gemäßigte Wassertemperaturen und planktonreiches Wasser vorausgesetzt erreichen die Muscheln bereits nach einem halben Jahr ihre Marktreife von 5 bis 6 cm. Die Muschelkulturen befinden sich in Bereichen, die bei Ebbe nicht trocken fallen. Damit sind die Muscheln beispielsweise für Austernfischer und Silbermöwen nicht erreichbar. Andere Arten, denen natürliche Muschelbänke Lebensraum bieten,

können den Muscheln ebenfalls nicht ins tiefere Wasser folgen. Außerdem werden die Kulturmuscheln regelmäßig von Aufwuchs gereinigt, und Fressfeinde wie Seesterne werden gefangen, damit sie den Ertrag nicht schmälern. Auch weil Kulturmuscheln bereits innerhalb eines Jahres geerntet werden, können sich zwischen ihnen keine angepassten Lebensgemeinschaften entwickeln. Der Appetit von vor allem Deutschen, Franzosen und Niederländern auf Miesmuscheln freut natürlich die Menschen, die von ihrem Verkauf leben. In Schleswig-Holstein wurde die Vergabe einer Fangerlaubnis von der Verarbeitung vor Ort mit den daran gebundenen Arbeitsplätzen abhängig gemacht. Die Nachfrage nach Muscheln ist größer als die Produktion. Deshalb würden die Muschelfischer die Kulturflächen gerne ausweiten, während die Naturschützer darauf drängen, größere Teile des Wattenmeers als Nationalpark auszuweisen und jegliche Nutzung zu unterbinden.

### **Aufgabe**

Zu einer öffentlichen Anhörung werden **Verbraucher**, **Muschelfischer** und **Naturschützer** geladen. Diskutiert wird die Frage: *Soll die Muschelfischerei in Randzonen des Nationalparks erlaubt oder gänzlich untersagt werden?*

Ein **Moderator** leitet die Diskussion. Zwei **Protokollanten** halten die Argumente, die von den drei Interessengruppen genannt werden, in Stichworten an der Tafel fest. Jeder von euch soll den Standpunkt einer der drei Interessengruppen vertreten. Achtet darauf, dass die Rollen gleich stark besetzt sind. Sucht nach überzeugenden Argumenten. Hilfreich sind Recherchen im Internet oder auch Nachfragen bei Naturschutzvereinen und Fischereibetrieben. Bei der Diskussion sollten alle Gruppen eine gewisse Kompromissbereitschaft zeigen.

Für die **Muschelfischer** ist der Job lebensnotwendig, weil der Verdienst ihre Familien ernährt. Oft haben schon viele Generationen vorher den gleichen Beruf ausgeübt, und diese Familientradition bedeutet ihnen viel. Zudem bietet ihr Wohnort kaum andere Arbeitsmöglichkeiten. Die Ausweisung des Nationalparks, der unter anderem die Muschelbänke schützen soll, schränkt ihre Fanggründe ein. Die Fischer fühlen sich bevormundet und reagieren mit großer Skepsis auf die Meinung der Naturschützer.

Die **Naturschützer** sehen das Ökosystem Wattenmeer in Gefahr. Sie möchten nicht nur die Muscheln selbst, sondern vor allem die Artenvielfalt auf den Muschelbänken bewahren. Sie sorgen sich um die Algen- und Tierarten, die auf Muschelbänken heimisch sind, und um Zugvögel wie die Eiderenten, die im Wattenmeer rasten und hier Nahrung suchen. Bei ihrem Einwand gegen die Muschelfischerei im Nationalpark versuchen sie, das Verständnis der Verbraucher zu gewinnen.

Die **Verbraucher** schätzen das Muschelfleisch als proteinreiche, kalorienarme Delikatesse. Besucher der Küstenregionen bevorzugen regional typische Speisen. Möglicherweise wären die Touristen bereit, höhere Preise für die Muscheln zu zahlen und damit eine nachhaltigere Fischerei zu unterstützen. Vielleicht ist es ihnen aber auch egal, was mit den Muscheln passiert – Hauptsache, sie verbringen schöne Urlaubstage am Meer und bekommen Muscheln auf den Tisch.

### **Informationen zur Haltung von Miesmuscheln**

Die Haltung von Miesmuscheln ist unkompliziert und erfordert einen geringen Materialaufwand. Ein Aquarium für etwa 30 Miesmuscheln sollte 30 bis 40 Liter fassen. Anstelle von frischem Meerwasser kann auch mit Salz angereichertes Leitungswasser verwendet werden. Wieviel Salz hinzugefügt werden sollte, richtet



sich nach der Herkunft der Muscheln (im Fischhandel erfragen), z. B. Nordsee: 20 – 30 g, Ostsee: 8 – 10 g, Kieler Bucht: etwa 15 g. Das Wasser wird über eine Pumpe mit Sprudelstein belüftet und mit einem einfachen Schwammfilter gereinigt. Die Wassertemperatur sollte 18 °C nicht überschreiten; daher muss das Becken kühl und halbschattig stehen. Wöchentlich sollten zwei Drittel des Wasser gewechselt werden. Als Futter eignen sich Algenflocken oder feines Fischaufzuchtpulver. Ein halber bis ein Teelöffel pro Woche genügt. Bei Verwendung von frischem Meerwasser ist weniger Futter nötig.

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# **ASSESSING SYSTEM THINKING THROUGH DIFFERENT CONCEPT-MAPPING PRACTICES**

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**Abstract**

System thinking is usually investigated by using questionnaires, video analysis, or interviews. Recently, concept-mapping (CM) was suggested as an adequate instrument for analysing students' system thinking. However, there are different ways with which to use this method. Therefore, the purpose of this study was to examine whether particular features of CM practices affect the valid assessment of students' system thinking. The particular features analysed were the medium (computer vs. paper-pencil) and the directedness (highly directed vs. nondirected) of CM practices. These features were evaluated with respect to their influence on (a) students' performance in CM and (b) the validity of different CM practices for system thinking. One hundred fifty-four German 4<sup>th</sup> graders (mean age: 9.95 years) and 93 8<sup>th</sup> graders (mean age: 14.07 years) participated in the study following an experimental pretest-posttest design. Three variations of CM practices were applied: (a) highly directed computer mapping, (b) highly directed paper-pencil mapping, and (c) nondirected paper-pencil mapping. In addition to the CM task, a paper-pencil questionnaire was employed to investigate the validity of the CM practices. Results showed that the computer positively influenced student performance in CM when compared to paper-pencil. By contrast, there was no difference between highly directed and nondirected mapping. Whereas the medium rarely influenced the validity of CM for system-thinking, high directedness showed a positive influence. Considering the limitations and benefits of particular CM practices, we suggest highly directed and computer-based CM as an appropriate assessment tool—in particular, with regard to large-scale assessments of system thinking.

## 1. Introduction

System thinking involves capturing a system as a 'whole through the interaction of its parts' (Assaraf & Orion, 2005, p. 550) and understanding a system's stability as cause-and-effect-loop related. The importance of system thinking for a meaningful understanding of science, and consequently, the investigation of school students' system thinking, has gone unquestioned among science education researchers over the past decade (Assaraf & Orion, 2010; Boersma, Waarlo, & Klaassen, 2011; Evagorou, Kostas Korfiatis, Nicolaou, & Constantinou, 2009; Hogan, 2000; Penner, 2000; Riess & Mischo, 2010; Sommer & Lücken, 2010). Science education at school still focuses on isolated facts rather than on systemic relationships and processes over time (Hannon & Ruth, 2000) that is teaching complex systems is principally not implied in obligatory education (Jacobson & Wilensky, 2006). Despite being noted as important, the integration of system thinking into education still can be described as limited (Jacobson & Wilensky, 2006; Plate, 2010).

A complex and dynamic system can be considered as composed of interdependent and interacting components that either can be physical like objects or intangible like processes, information flows, relationships, feelings, values or beliefs (Anderson & Johnson, 1997). System thinking can be defined as ability to understand the multilevel structure of those numerous components, their dynamic and nonlinear relationships (Hmelo-Silver & Azevedo, 2006). This mental acquisition of complex accumulation processes requires a wide amount of cognitive abilities, compassing the structural as well as the inflective analysis of complex systemic behavior (Richmond, 1993, Sterman, 2010).

This two-dimensional way of intellectually coping with dynamic systems is described as , structural and procedural system thinking (Sommer & Lücken, 2010). *Structural system thinking* is the ability to identify a system's relevant elements and their interrelationships, altogether determining the system's framework. It refers to analysing the basic structure of a system, which means to be able to define those elements or objects that count for the systems' identity. Accordingly, structural system thinking is characterized by the ability to distinguish the relevant system from other surrounding systems precisely. *Procedural system thinking* is the ability to understand the dynamic and time-related processes that emerge from the systems' structure, particularly occurring in within systems' elements and subsystems. These interacting elements and subsystems can be considered as microscopic level that is causally linked with the macroscopic level of complex system properties often occurring simultaneously and with indirect causality (Sterman, 2008). This two-dimensional characterization (structural and procedural system thinking) relates to the model of system thinking suggested by Assaraf and Orion (2005). They theoretically characterize system thinking as ability that comprises the understanding of the basic organizational framework of relationships as first dimension (here, structural system thinking) and the understanding of the cyclic and dynamic relationship development within the system - including retrospective and predictive thinking about a system's cyclic nature - as second dimension (here, procedural system thinking).

Among experts, there is no consensus concerning the appropriate moment for the introduction of system thinking at school. Some emphasize the introduction of system thinking as early as possible, referring to empirical studies that give some evidence that elementary school children are capable of basic system thinking (e.g.

Assaraf & Orion, 2010; Evagorou et al., 2009; Sommer & Lücken, 2010). Others argue that system thinking - as it is necessary to reconstruct complex systemic processes - implicates higher order thinking skills (e.g. Frank, 2000). These skills seem to be underdeveloped even at university-age. Jacobson and Wilensky (2006) for example, state that many university-age students also tend toward simple causal explanatory statements rather than toward the reconstruction of complex systemic processes. Nevertheless, Boersma et al. (2011) recommend imparting system thinking in primary and secondary school education to provide students with basic cognitive structures such as causality, form-function relation and part-whole relation corresponding to systems concepts. However, irrespectively of the education level, there is a need for suitable system thinking assessment instruments; otherwise, the investigation of system thinking development might be difficult. Boersma et al. (2011) claim that there is a lack of appropriate system thinking assessments in primary and lower secondary school, particularly the assessment of “forward and backward thinking between concrete objects and system models” (p. 190). Consequently, more research is needed to establish appropriate assessment instruments in order to provide sufficient information about the development of system thinking. As researchers have stated that the development of such assessment tools is at an early stage, there is a need for instruments that are applicable to large groups of students, and if elementary students are at the focus of attention, there is also a need for a method of conveyance that is easy for young children to understand (e.g. Boersma et al., 2011; Jacobson & Wilensky, 2006).

Prior research has shown that system thinking captured through different approaches, for example, computer-based programming environments, interviews, videotaped classroom discussions, and paper-pencil tools (Assaraf & Orion, 2010;



Evagorou et al., 2009). Recently, *concept-mapping* (CM) was suggested to be an adequate instrument for analysing students' system thinking (Sommer & Lücken, 2010), but there is no general agreement about the appropriate CM practice to assess system thinking.

### **1.1. Mental models, CM, and System Thinking Assessment**

Mental models are internal cognitive representations of ideas, events, objects, or systems used in generating external representations (Brewer 1987). These mental models result from an internal modelling process including the drawing of new information on existing knowledge to build a stable model, a process that continually involves the revision or rejection of some phenomenon or system. . Related to a psychological understanding of mental models, each known fact or connection between facts is a probable allegation (Seel, 2001). External representations of mental models are used to evaluate not only conceptual understanding but also the ability to solve problems in a complex systems' content (Johnson-Laird, 2001). Particularly with respect to the understanding of biological phenomena that are complex and nonlinearly organized, the external representation of mental models is a helpful approach to the multilevel structure that biological phenomena include (Boulter & Buckley, 2000; Buckley & Boulter, 2000). Concept maps are external representations of mental models, consisting of concepts (nodes) connected to each other by labelled lines, in each case building a proposition (Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005). The concept map's structure is due to the orientation and arrangement of the linking lines, forming a hierarchical or non-hierarchical net structure (Yin et al., 2005) that can be considered as representation of a mental model. Therefore, CM is considered to be an adequate tool to assess mental models

in the form of conceptual understanding in science (Assaraf & Orion, 2010; Evagorou et al., 2009; Mintzes, Wandersee, & Novak, 1998; Ruiz-Primo & Shavelson, 1996). As system thinking implies the conceptual understanding of the underlying system structure, which leads to the unfolding of systems' behaviour, CM is helpful to evaluate the internal system structure.

Following Sommer and Lücken (2010), who suggested CM to be adequate instruments for analysing students' system thinking, in our study, CM was applied to analyse students' system thinking. In science education research, different types of CM practices are employed, characterized by the medium (computer based or paper-pencil based) used to construct the map and the degree of directedness of the CM practice (highly directed CM practice: concepts and linking words are given; nondirected CM practice: concepts and linking words are withheld; Ruiz-Primo, 2004). Computer based mapping offers easy manipulation through the dynamic linking of concepts, which is important for the mapping process itself that requires constant revision (Anderson-Inman & Zeitz, 1993; Plotnick, 1997). Thus, the risk of getting knotted up in a paper-pencil map might be conceivable especially with respect to primary students, who might have difficulties in clearly subdividing the map. Correspondingly, Royer and Royer (2004) investigated how computer mapping and paper-pencil mapping influence the degree of complexity of students' concept maps. Results show that computer mapping results in a considerably higher complexity than paper-pencil mapping. Furthermore, Royer and Royer (2004) showed that students definitely prefer to construct concept maps by the computer. This result was confirmed by teachers that observed motivational benefits of their students during computer mapping.

Because little is known so far about suitable CM practices for assessing students' system thinking, the aim of our study was to analyse which CM practice fits best for assessing students' procedural and structural system thinking ability. In detail, the influence of the medium and the directedness on CM performance and the validity of different CM practices for procedural and structural system thinking assessment were investigated. Comparing different CM practices provides important information about suitable system thinking assessments, especially for younger students within the context of large-scale assessments.

Against this background, the following research questions were developed:

1. *Does the medium (computer vs. paper-pencil) and/or the directedness (highly vs. nondirected) influence students' performance in CM?*
2. *Does the medium (computer vs. paper-pencil) and/or the directedness (highly vs. nondirected) influence the validity of students' CM regarding procedural and structural system thinking?*

## **2. Method**

### **2.1. Sample and Design**

An experimental pretest-posttest study was conducted in seven fourth-grade science classes from five German primary schools and four eighth-grade biology classes from three German secondary schools. Fourth graders ( $n = 154$ ) were 9 to 11 years old (mean age: 9.95 years;  $SD = 0.62$ ). Eighth graders ( $n = 93$ ) were between 13 and 15 years of age (mean age: 14.07 years;  $SD = 0.46$ ). Gender was distributed evenly in the fourth and eighth grades: 46.5% of fourth graders and 51.1% of eighth graders were male.

Students were randomly allocated to different experimental conditions, each corresponding to a particular CM practice. CM practices result from two factors. (a) The degree of directedness is the first factor, which has two levels (highly directed and nondirected). A high degree of directedness is characterized by the constraint to construct concept maps by a given set of concepts and linking words. The set of concepts was derived from four experts' (biologists and science educators) concept maps describing 'Development, enemies, living, and feeding of eggs, larvae, young and adult blue mussels.' Then these concepts were used for the construction of an additional concept map by the authors. Afterwards, this concept map was revised by the experts. After consensus was achieved between the experts and the authors, the final concept map consisted of a set of 11 concepts (e.g. blue mussel, sea star) and 10 linking words (e.g. feed, protect; see Appendix A). By contrast, a minimal degree of directedness (i.e. nondirected) is characterized by having no constraints regarding number and choice of concepts and linking words. That is, students configured their own set of concepts and linking words. (b) The medium as the second factor can be differentiated into two levels (computer and paper-pencil) as well. Computer maps were constructed using the software package MaNET<sup>®</sup>. The MaNET<sup>®</sup> user interface contains a given set of concepts, and a given set of linking words is presented in a pop-up window. Because MaNET<sup>®</sup> does not allow for having a minimal degree of directedness (i.e. nondirected), we did not use the experimental condition 'nondirected computer mapping' for the MaNET<sup>®</sup> condition. Paper-pencil maps were constructed on a large paper sheet (11.69 x 16.54 in). Similar to MaNET<sup>®</sup>, the upper left corner of the sheet contained the set of concepts for a high level of directedness. The set of linking words, by contrast, was presented on a separate small paper sheet (5.83 x 8.27 in) similar to the MaNET<sup>®</sup> pop-up window. For a minimal level of

directedness (i.e. nondirected), neither the large nor the small paper sheet contained any concepts or linking words. Thus, the incomplete factorial design of our study had three experimental conditions: (a) highly directed computer mapping, (b) highly directed paper-pencil mapping, and (c) nondirected paper-pencil mapping.

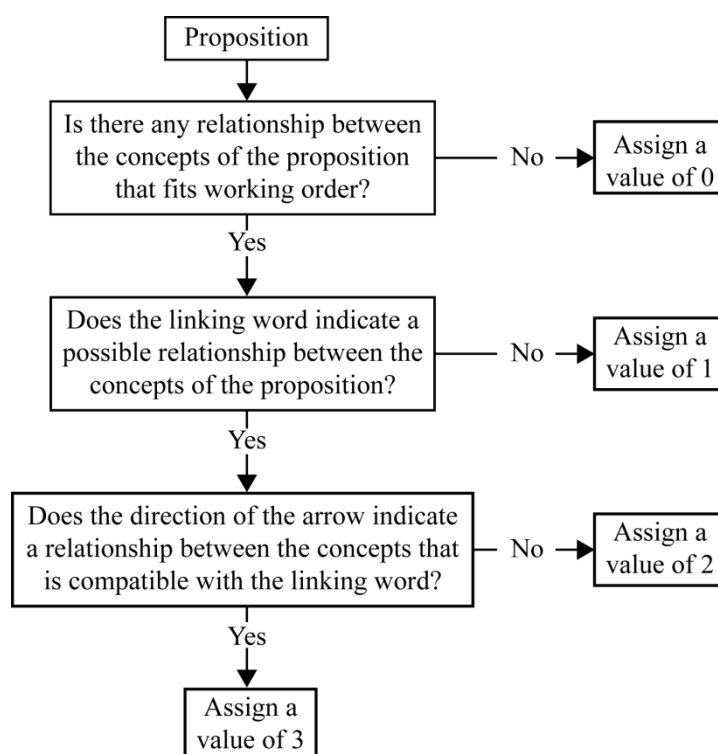
## **2.2. Dependent Variables**

**Procedural and Structural System Thinking.** A questionnaire was developed to capture procedural and structural system thinking (see Appendix B and C, respectively). The questionnaire contained four open questions and 15 multiple-choice questions. Six multiple-choice questions were offered to the students to assess procedural system thinking. Nine multiple-choice questions and the open questions were offered to the students to assess structural system thinking. Relating to the theoretical two-dimensional model of system thinking, the questions to assess procedural system thinking were constructed to capture the ability to understand possible processes and behaviours within the system (e.g.: “Oysters are much stronger than Blue Mussels. Imagine Oysters displacing the mussels in a few years. What are the consequences for eider ducks?”). The questions to assess structural system thinking were constructed to capture the ability to identify relevant system elements, simple relationships between facts (e.g., “How do Blue Mussels protect themselves from heat at low tide?”) and to understand systems’ separation from other surrounding systems. (e.g., “Which of these terms are irrelevant for a Blue Mussel’s life? Strike them out! Sea Star, foot, sand, human, air, water, oxygen, shell”). For each of the questions, a maximum score of 3 to 16 points could be reached.

In order to provide some evidence that the questionnaire assessed two different dimensions of system thinking that efforts students to activate either procedural or structural system thinking, two independent experts decided whether questions are indicators for procedural or structural system thinking. Afterwards, unadjusted intraclass correlations were calculated between experts' decisions and authors' allocations. Calculations show that experts and authors agree in a considerable proportion which question is an indicator for procedural or structural system thinking. The intraclass correlation coefficient (*ICC*) is notably high,  $ICC = 0.947$ , which indicates that questions validly capture procedural and structural system thinking, respectively.

**CM performance.** Concept maps were scored according to the relational scoring method developed by McClure, Sonak, and Suen (1999). This method is suitable for analysing all concept maps used in this study regardless of the particular CM practice. By using the relational scoring method, raters scored an individual concept map concerning the correctness of its propositions, which is defined through two concepts (e.g. 'sea star,' 'blue mussel') connected by a labelled arrow (e.g. 'feed'), the reading direction and the relationship between these concepts. A scoring protocol (see Figure 1) was used to score the correctness of each proposition by assigning a value from zero to three. In accordance with this scoring protocol, a value of zero is assigned if a student connects two concepts that have low or no semantic similarity (e.g. 'eider duck' and 'sea star'). A value of zero is also assigned if two concepts have semantic similarity (e.g. 'eider duck' and 'egg') but are not relevant to the task (e.g. 'eider duck lays egg'). A value of one is assigned if the linking word (connecting two concepts) does not describe the relationship between the concepts in a semantically correct fashion (incorrect: 'oyster feeds blue mussel'; correct: 'oyster

displaces blue mussel’). A value of two is assigned if the linking word explaining the relationship between two concepts is semantically correct but the reading direction indicated by the arrow is wrong (incorrect: ‘sea star <-- feeds -- blue mussel’; correct: ‘sea star -- feeds --> blue mussel’). Finally, a value of three is assigned if the proposition is entirely correct. The sum of all separate propositions provides the final score for the particular concept map.



**Figure 1:** Scoring protocol for scoring separate propositions (adapted from McClure et al., 1999).

Interrater reliability was separately determined for conditions (a), (b), and (c). Within each condition, 15% of the concept maps were scored by two raters. Raters' individual proposition scores were compared by calculating unadjusted intraclass correlations. *ICCs* were high for all conditions. For condition (a), an *ICC* of 0.982 was computed. The *ICCs* for conditions (b) and (c) were 0.968 and 0.920, respectively.

### **2.3. Procedure and Materials**

The study took place in students' regular classrooms. The instructor conducted a 35-min unit introducing students to CM. This unit consisted of a 15-min theoretical part and a 20-min practical part. The theoretical part focused on providing (meta-) cognitive strategy knowledge, for example, concept maps were explained to be diagrams representing ideas as node-link assemblies. The diagrams were described as composed of concepts interrelated to each other by labelled arrows in a meaningful way. The instructor demonstrated on the blackboard how to design a CM. After the theoretical part was finished, students were randomly assigned to the three experimental conditions, and the practical part followed. Depending on the particular experimental condition, students received different verbal and written instructions. Instructions were different according to the particular CM practice students attended (e.g. to use computer software in condition [a] or to select relevant concepts in condition [c]). However, they were identical regarding the work order, namely, to construct a concept map that describes the relationship of different persons working in school or attending school. Beyond that, students obtained the same material they had been given for the pretest and posttest to construct their concept maps (e.g. laptop, large and small paper sheet, pencil). To ensure that every student was able to handle the practice, the whole practical part was supervised by the instructor.

The following lesson—the pretest—was administered by the instructor. The pretest consisted of a 20-min questionnaire as well as a 20-min CM practice. CM practices differed between experimental conditions. However, all students were given the assignment to construct a concept map describing the 'Development, enemies, living, and feeding of eggs, larvae, young and adult blue mussels.' Students constructing nondirected paper-pencil maps were not given further instructions. Students

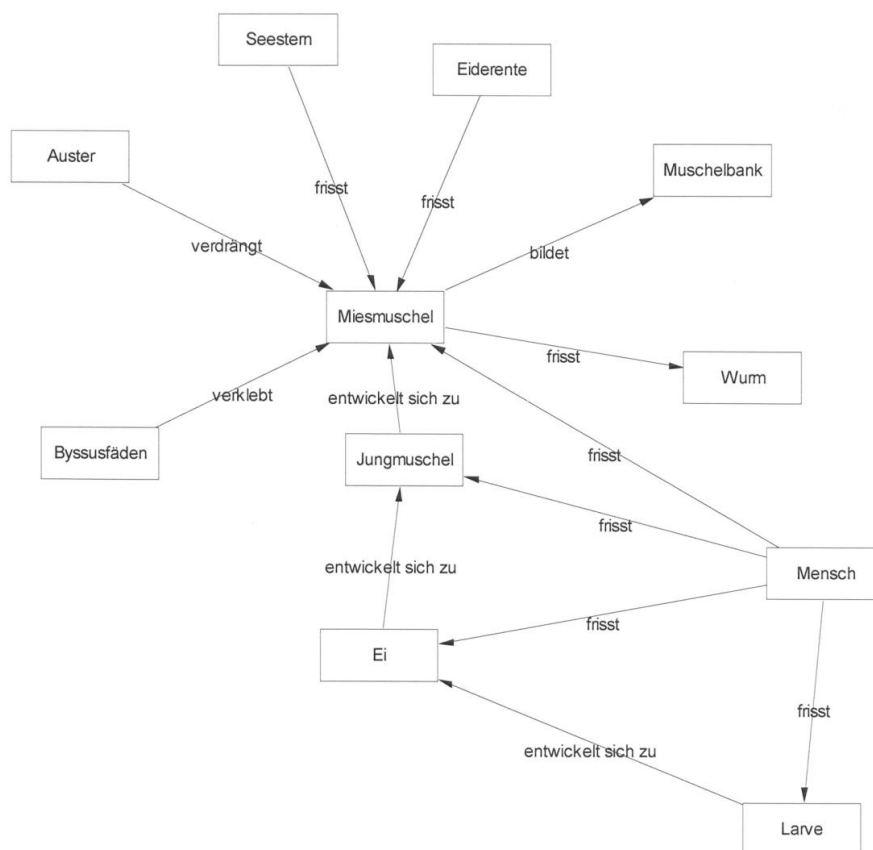


constructing highly directed concept maps either by computer or paper-pencil were presented with the selected 11 concepts and 10 linking words.

The following Lessons 1 to 6 took place in students' classrooms. Students' regular science or biology teachers taught 'Development, enemies, living, and feeding of eggs, larvae, young and adult blue mussels.' The content 'blue mussel' was chosen in order to serve an intervention unit that is not obligatorily part of the curriculum but comprises a high relevance regarding the local situation in Schleswig Holstein that is framed by the Wadden Sea at the western coast side of Germany. Therefore, it was possible to provide each classroom with 'living material'. For that purpose, teachers had to use an aquarium and teaching material that was provided by the instructor. Teachers were requested to adhere to teaching material, and they were directed to report whether they deviated from the teaching material. Based on teachers' reports, we concluded that teachers closely adhered to the teaching material and their deviations were minimal. At this point, it is important to note that none of the teachers constructed concept maps during the phase of blue mussel lessons. In Lesson 7, the instructor visited students again and administered the posttest. Analogous to the pretest the posttest consisted of a 20-min questionnaire and the same 20-min CM practice as in the pretest.

### 3. Results

The first aim of our study was to investigate whether the medium (computer vs. paper-pencil) and/or the directedness (highly vs. nondirected) of the CM tasks influenced students' CM performance. Examples for students' concept maps arising from experimental conditions 'highly directed computer mapping', 'highly directed paper-pencil mapping', and 'nondirected paper-pencil mapping' are shown in Figure 2, 3, and 4. Each concept map was constructed in grade 4 (posttest) and earned the median proposition accuracy score from the respective experimental condition. Median proposition accuracy score in condition 'highly directed computer mapping' was 23, in condition 'highly directed paper-pencil mapping' was 12, and in condition 'nondirected paper-pencil mapping' was 14.



**Figure 2:** Example for 'highly directed computer mapping'

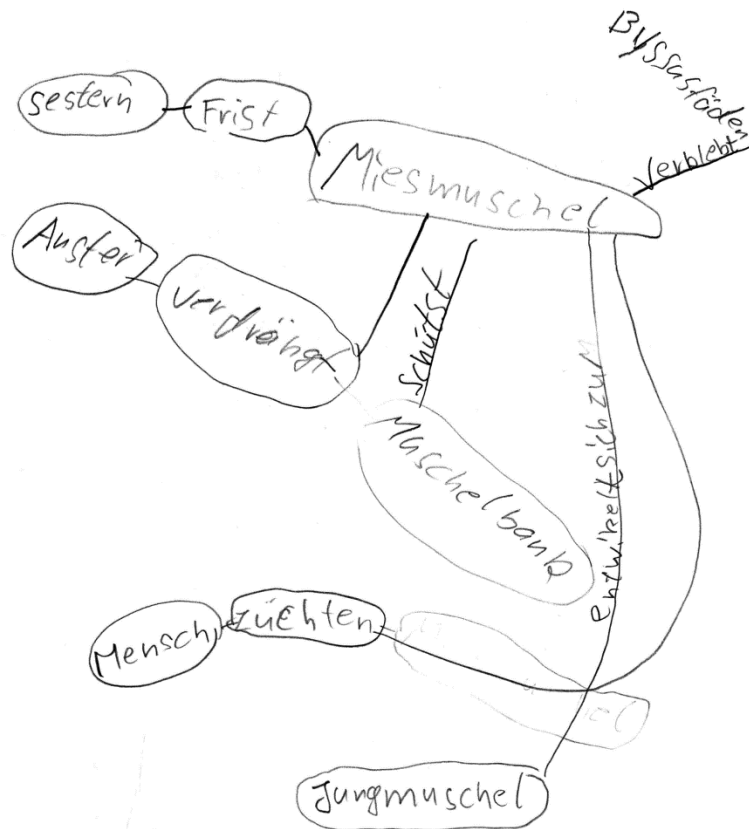


Figure 3: Example for 'highly directed paper-pencil mapping'

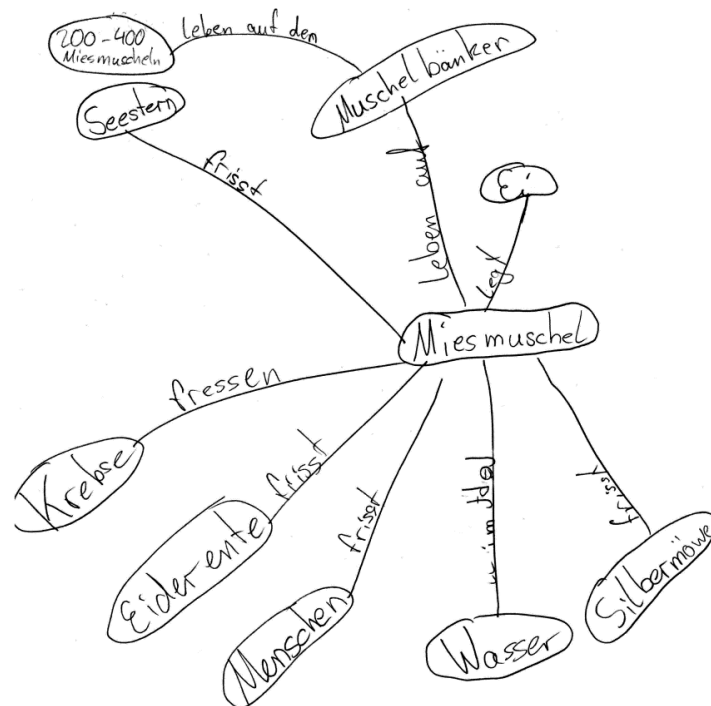


Figure 4: Example for 'nondirected paper-pencil mapping'

The second aim was to determine whether the medium and/or the directedness influenced the validity of students' concept maps for procedural and structural system thinking ability. For this purpose, procedural and structural system thinking scales were developed. The following paragraph shows that each scale actually captured different aspects of system thinking. Afterwards, we show that experimental conditions were equal regarding performance on the pretest. We finish our explanations by answering the research questions.

### **3.1. Confirmatory Factor Analysis (CFA)**

CFA is used to study the relation between a set of observed variables (e.g. a set of items) and a set of continuous latent variables (i.e., factors). We hypothesized that a two-factor model would explain students' responses to a set of 19 items. Six items were used as indicators for the first factor representing procedural system thinking ability (see Appendix B); the remaining 13 items were used as indicators for the second factor representing structural system thinking ability (see Appendix C). We conducted CFA for continuous variables using the structural equation software MPlus 5.21 (Muthén & Muthén, 2007). Maximum likelihood estimation with robust standard errors was chosen to investigate whether our data could be explained by two correlated factors. Our analysis was based on data from 423 students (298 fourth graders and 125 eighth graders). 154 fourth graders and 93 eighth graders were part of the present study. The remaining 176 students attended the same unit (topic 'blue mussels') but solved the procedural and structural system thinking questionnaires without constructing concept maps concomitantly. There were no missing data. We estimated the hypothesized two-factor model and an alternative one-factor model with the underlying assumption that system thinking may be represented through a

whole undivided factor. Table 1 shows that goodness-of-fit indices for the two-factor model outperformed fit indices for the one-factor model. Relating to the two-factor model, the relative  $\chi^2$  was less than 2 (Ullman, 2001), the comparative fit index (CFI) exceeded 0.90 (Homburg & Baumgartner, 1996), the Tucker-Lewis fit index (TLI) exceeded 0.90 (Homburg & Baumgartner, 1996), and the RMSEA was less than 0.06 (Hu & Bentler, 1999). To test whether the two-factor model explained students' responses to the set of items significantly better than the one-factor model, we computed the scaled  $\chi^2$  statistic according to Satorra and Bentler (1999). This test indeed showed that the two-factor model fit significantly better than the one-factor model ( $TRd = 22.25$ ,  $\Delta df = 1$ ;  $p < 0.001$ ). No post hoc modifications were indicated from the analysis because the goodness-of-fit indices for the two-factor model and the residual analysis did not indicate any problems.

**Table 1:** Goodness-of-Fit Indices for Two Models (N = 423)

Model	<i>df</i>	$\chi^2$	$\chi^2/df$	CFI	TLI	RMSEA	AIC
Single factor	152	305.64	2.01	0.89	0.88	0.05	18544.88
Two factor	151	271.51	1.80	0.91	0.90	0.04	18510.25

*Note.*  $\chi^2/df$  = relative chi-square; CFI = comparative fit index; TLI = Tucker-Lewis fit index; RMSEA = root-mean-square error of approximation. AIC = Akaike information criterion; modified: residual correlation between two items admitted.

In order to quantify students' procedural and structural system thinking abilities, sum scores of the particular items were calculated for each student. The sum of the six items representing the first factor is a measure for students' procedural system

thinking ability; the sum of the remaining 13 items representing the second factor quantifies students' structural system thinking ability. Cronbach's alphas for procedural and structural system thinking were 0.85 and 0.71, indicating that the scales had acceptable internal consistency.

### 3.2. Preliminary Analyses

An alpha level of 0.05 was used for all statistical analyses. Kolmogorov-Smirnov tests indicated that proposition accuracy scores, procedural system thinking scores, and structural system thinking scores were not significantly different from a normal distribution. Levene's test approved homogeneity of variance between experimental conditions regarding proposition accuracy scores, procedural system thinking scores, and structural system thinking scores. Beyond that, we analysed students' procedural and structural system thinking scores depending on their affiliations with different experimental conditions (highly directed computer mapping, highly directed paper-pencil mapping, and nondirected paper-pencil mapping). Because students were randomly assigned to experimental conditions, we did not expect differences between conditions on the pretest. Multivariate analysis of variance (MANOVA) with students' procedural and structural system thinking scores (pretest variables) as dependent variables and experimental condition as a between-subjects factor confirmed our expectation. Experimental conditions did not significantly differ on the pretest in Grade 4,  $F(4, 212) = 0.73$ ,  $p = 0.573$ , *partial*  $\eta^2 = 0.01$ , Wilks's  $\lambda = 0.97$ , and Grade 8,  $F(4, 142) = 0.16$ ,  $p = 0.957$ , *partial*  $\eta^2 = 0.01$ , Wilks's  $\lambda = 0.99$ . Because the same measurement instruments (concept maps, procedural, and structural system thinking questionnaires) were employed in the fourth and eighth grades, we looked for floor and ceiling effects by using

histograms. Neither of them occurred on the pretest or posttest in the fourth or eighth grade. Nevertheless, we restricted following analysis to posttest scores only because students' knowledge about the blue mussel was much better after the phase of blue mussel lessons.

### **3.3. Students' CM Performance**

Our first research question focused on students' CM performance as a function of experimental condition. Table 2 shows that students who constructed highly directed computer maps outperformed those students who constructed highly directed paper-pencil maps. One-way analysis of variance (ANOVA) was performed to check for differences between our experimental conditions in Grades 4 and 8. Proposition accuracy scores (posttest variable) served as the dependent variable. Experimental condition served as a between-subjects factor. The ANOVA indicated significant differences in the mean proposition accuracy scores across experimental conditions in Grade 4,  $F(2, 99) = 19.67, p < 0.001, \text{partial } \eta^2 = 0.28$ , and in Grade 8,  $F(2, 59) = 6.39, p = 0.003, \text{partial } \eta^2 = 0.18$ . However, we still did not know which experimental conditions differed in their mean proposition accuracy scores. Therefore, we performed pairwise comparisons using Gabriel's post hoc procedure, which has good power and can be used when sample sizes are slightly different (Field, 2009).

**Table 2:** Mean Proposition Accuracy Posttest and Standard Deviations as a Function of Experimental Condition and Grade

Grade	Experimental condition								
	Highly directed computer-mapping			Highly directed paper- pencil mapping			Nondirected paper- pencil mapping		
	(a)			(b)			(c)		
	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>
Four	22.00 <sub>a</sub>	5.82	35	12.76 <sub>b</sub>	7.36	34	13.52 <sub>b</sub>	7.14	33
Eight	28.29 <sub>a</sub>	6.58	17	20.87 <sub>b</sub>	9.51	23	18.32 <sub>b</sub>	9.61	22

*Note.* Mean scores marked by different subscripts differ significantly in post hoc analyses.

### 3.4. Influence of Medium on CM Performance

First, we were interested in whether medium (computer vs. paper-pencil) influenced students' CM performance. To answer this question, highly directed computer mappers were compared with highly directed paper-pencil mappers using Gabriel's post hoc procedure. Results indicated that highly directed computer mappers ( $M = 22.00$ ,  $SD = 5.82$ ) performed significantly better ( $p < 0.001$ ) than highly directed paper-pencil mappers ( $M = 12.76$ ,  $SD = 7.36$ ) in Grade 4. In Grade 8, a similar result was observed (see Table 2). Gabriel's post hoc procedure also indicated that highly directed computer mappers ( $M = 28.29$ ,  $SD = 6.58$ ) performed significantly better ( $p = 0.032$ ) than highly directed paper-pencil mappers ( $M = 20.87$ ,  $SD = 9.51$ ). To summarize the first section, using the computer as the medium for CM improved student performance.



### **3.5. Influence of Directedness on CM Performance**

Our previous analyses showed that medium influenced students' CM performance. Second, we were interested in whether directedness (high directed vs. nondirected) influenced students' CM performance. For this purpose, highly directed paper-pencil mappers were compared to nondirected paper-pencil mappers using Gabriel's post hoc procedure. Results indicated that in Grade 4 as well as in Grade 8, directedness did not influence students' CM performance (see Table 2). Highly directed paper-pencil mappers ( $M = 12.76$ ,  $SD = 7.36$ ) performed just as well ( $p = 0.957$ ) as nondirected paper-pencil mappers ( $M = 13.52$ ,  $SD = 7.14$ ) in Grade 4. In Grade 8, a consistent result was observed. Gabriel's post hoc procedure also revealed that highly directed paper-pencil mappers ( $M = 20.87$ ,  $SD = 9.51$ ) did not differ significantly ( $p = 0.706$ ) from nondirected paper-pencil mappers ( $M = 18.32$ ,  $SD = 9.61$ ). The results for the second section indicated that directedness did not influence student performance in CM.

### **3.6. Validity of Proposition Accuracy Scores Resulting from Different CM Practices**

Our second research question referred to the validity of students' proposition accuracy scores for procedural and structural system thinking abilities as a function of experimental condition. As a measure of validity, product moment correlations were calculated between proposition accuracy scores and procedural system thinking scores as well as between proposition accuracy scores and structural system thinking scores. Large correlation coefficients between proposition accuracy scores and procedural or structural system thinking scores would provide evidence that proposition accuracy scores validly capture procedural or structural system thinking

ability. Small correlation coefficients would indicate that proposition accuracy scores are not appropriate for capturing procedural or structural system thinking ability.

Because the difference between correlation coefficients cannot be regarded as an appropriate measure of effect size, the effect size index  $q$  was computed for comparing correlation coefficients (Cohen, 1983). The effect size index  $q$  is calculated by transforming  $r_1$  and  $r_2$  into  $z_1$  and  $z_2$ , respectively, by using Fisher's  $z$  transformations. Fisher's  $z$  transformation is conducted by computing the following relation  $z = \frac{1}{2} \log_e \frac{1+r}{1-r}$ . Using  $z$ -values, the effect size index  $q$  is calculated according to  $q = |z_1 - z_2|$ . Cohen (1983) provides bench marks for  $q$  values. A value of  $q = 0.10$  is defined as a small effect, a value of  $q = 0.30$  as a medium effect, and a value of  $q = 0.50$  indicates a large effect. Because of small sample sizes and low power, differences between correlation coefficients are considered by using the effect size index  $q$  only. A test for statistical inference such as calculating confidence intervals for the difference between the correlations of two samples according to Olkin and Finn (1995) is not reported.

### **3.7. Influence of Medium on the Validity of Proposition Accuracy Scores for Procedural System Thinking Ability**

First, we analysed the influence of medium (computer vs. paper-pencil) on the validity of students' proposition accuracy scores for procedural system thinking ability. For this, posttest correlations between proposition accuracy scores and procedural system thinking scores were calculated and compared between the experimental conditions highly directed computer mapping and highly directed paper-pencil mapping. In Grade 4, there was no difference between correlation coefficients ( $q = 0.05$ ), whereas in Grade 8, a medium effect was observed ( $q = 0.30$ ; see Table

3). The results indicated that medium does not influence the validity of proposition accuracy scores for procedural system thinking ability in Grade 4, whereas proposition accuracy scores resulting from highly directed paper-pencil maps ( $r = 0.73^{***}$ ,  $n = 23$ ) have higher validity for procedural system thinking ability in Grade 8 than proposition accuracy scores resulting from highly directed computer maps ( $r = 0.56^*$ ,  $n = 17$ ).

**Table 3:** Product Moment Correlations between Proposition Accuracy Scores and PST Scores and SST Scores (Posttest Variables)

	PST		SST	
	Grade 4	Grade 8	Grade 4	Grade 8
Experimental condition				
Highly directed computer mapping	0.59 <sup>***</sup> ( $n = 34$ )	0.56 <sup>*</sup> ( $n = 17$ )	0.27 ( $n = 34$ )	0.58 <sup>*</sup> ( $n = 17$ )
Highly directed paper-pencil mapping	0.62 <sup>***</sup> ( $n = 33$ )	0.73 <sup>***</sup> ( $n = 23$ )	0.56 <sup>***</sup> ( $n = 33$ )	0.74 <sup>***</sup> ( $n = 23$ )
Nondirected paper-pencil mapping	0.35 ( $n = 32$ )	0.41 ( $n = 22$ )	0.27 ( $n = 32$ )	0.61 <sup>**</sup> ( $n = 22$ )

\* $p < 0.05$ . \*\* $p < 0.01$ . \*\*\* $p < 0.001$ .

### **3.8. Influence of Medium on Validity of Proposition Accuracy Scores for Structural System Thinking Ability**

Second, we related the influence of medium (computer vs. paper-pencil) to the validity of students' proposition accuracy scores for structural system thinking ability. Therefore, posttest correlations between proposition accuracy scores and structural system thinking scores were calculated and compared between the experimental conditions highly directed computer mapping and highly directed paper-pencil mapping. In Grade 4, a mean effect of medium on correlation coefficients ( $q = 0.38$ ) was observed, whereas in Grade 8, there was a small effect ( $q = 0.28$ ; see Table 3) only. The results indicated that constructing concept maps by paper-pencil was positively related to the validity of proposition accuracy scores for structural system thinking ability both in Grade 4 ( $r = 0.56^{***}$ ,  $n = 33$ ) and in Grade 8 ( $r = 0.74^{***}$ ,  $n = 23$ ) when compared to constructing concept maps on the computer ( $r = 0.27$ ,  $n = 34$ , and  $r = 0.59^*$ ,  $n = 17$ , respectively).

### **3.9. Influence of Directedness on Validity of Proposition Accuracy Scores for Procedural System Thinking Ability**

Third, we focused on the influence of directedness (highly directed vs. nondirected) of a CM task on validity of students' proposition accuracy scores for procedural system thinking ability. Thus posttest correlations between proposition accuracy scores and procedural system thinking scores were calculated and compared between the experimental conditions highly directed paper-pencil mapping and nondirected paper-pencil mapping. Both in Grade 4 (medium effect:  $q = 0.37$ ) and in Grade 8 (high effect:  $q = 0.50$ ), proposition accuracy scores revealed higher validity for procedural system thinking ability in the condition highly directed paper-

pencil mapping ( $r = 0.62^{***}$ ,  $n = 33$ , and  $r = 0.73^{***}$ ,  $n = 24$ , respectively) than in the condition nondirected paper-pencil mapping ( $r = 0.35$ ,  $n = 32$ , and  $r = 0.41$ ,  $n = 22$ , respectively; see Table 3). The results indicated that providing concepts and linking words (highly directed) positively influenced the validity of proposition accuracy scores for procedural system thinking ability when compared to denying concepts and linking words (nondirected).

### **3.10. Influence of Directedness on Validity of Proposition Accuracy Scores for Structural System Thinking Ability**

Finally, we analysed the effect of directedness (highly directed vs. nondirected) of a CM task on the validity of students' proposition accuracy scores for structural system thinking ability. To address the research question, correlations between proposition accuracy scores and structural system thinking scores were compared between the experimental conditions highly directed paper-pencil mapping and nondirected paper-pencil mapping. Both in Grade 4 (medium effect:  $q = 0.35$ ) and in Grade 8 (small effect:  $q = 0.24$ ), proposition accuracy scores had higher validity for structural system thinking ability in the condition highly directed paper-pencil mapping ( $r = 0.56^{***}$ ,  $n = 33$ , and  $r = 0.74^{***}$ ,  $n = 23$ , respectively) than in the condition nondirected paper-pencil mapping ( $r = 0.27$ ,  $n = 32$ , and  $r = 0.61^{***}$ ,  $n = 23$ , respectively; see Table 3). That is, providing concepts and linking words was positively related to the validity of proposition accuracy scores for structural system thinking ability when compared to withholding concepts and linking words.

## **4. Discussion**

### **4.1. Influence of Medium and Directedness on Student Performance in CM**

The first aim of our study was to elucidate the effect of medium and directedness on CM performance in Grades 4 and 8. Concerning the medium, we expected that computer mapping would be challenging for elementary students. Against our expectations, handling CM with the computer was no obstacle for successful mapping, neither for fourth nor for eighth graders. Our results showed that both fourth and eighth graders performed significantly better when using the computer-based practice. These findings go along with those of Royer and Royer (2004) who showed that students using software to construct concept maps created maps with higher complexity than those who created paper-pencil ones. In fact, difficulties, such as the lacking possibility of easy manipulation, occurring during paper-pencil mapping might overbalance those occurring during computer mapping. Even though the particular paper-pencil mapping practice also includes the concepts and linking words (highly directed), it is still a demanding task to hierarchically structure the paper and to keep the general idea behind the mapping process. In particular, the hierarchy criterion requires the incorporation of new or more detailed information under more general concepts, which implies a clearly arranged mapping structure. The point of clear arrangement, which is brought by Paas (1992) as helpful to avoid overloading students, is obviously easier to come up with in the computer-based practice than in the paper-pencil practice. Thus, we can assume that if a student has a tool at his disposal, and this tool facilitates the creation of maps that are more complex and easier to organize, he will perform better than with paper-pencil maps. It follows that computer-based mapping, apart from being much more efficient to revise, might reveal more realistic insight into students' cognitive structure.

Interestingly, the effect of structural support through computer mapping appears particularly in the group of elementary students. This effect may be rooted in a different need for support depending on cognitive abilities that are age-related. Because eighth graders can be regarded as ‘higher achievers’ to the degree of their general cognitive abilities, this might be an explanation for the higher benefit of computer mapping as a supporting practice for fourth graders. As Kintsch (1990) reports about mental representations, the ‘higher achiever’ uses supporting strategies less frequently than the ‘lower achiever’ because the ‘higher achiever’ doesn’t feel the need to.

With respect to the influence of directedness (highly directed vs. nondirected) on CM performance in Grades 4 and 8, our results show no significant difference between highly and nondirected CM practices in both grades. To explain the lacking difference in mapping performance in favor of highly directed mapping, we stress the confusing complexity of creating paper-pencil maps, which could have interfered with the complete illustration of their knowledge. Possibly, the degree of directedness in this case plays a less important role according to mapping performance than the confusing complexity through paper-pencil mapping, which might be more challenging.

#### **4.2. The Influence of Medium and Directedness on the Validity of the CM Task**

The second aim of the study was to elucidate the validity of the different CM practices for capturing procedural and structural system thinking. As our results concerning the CM performance were significantly better for computer-based mapping, it was self-evident that similar effects could be assumed for the result

regarding the validity. However, our results surprisingly indicated that the medium rarely influenced the validity of performance scores for structural system thinking in Grade 4 and for both procedural and structural system thinking in Grade 8. There was no effect of the medium concerning procedural system thinking in the fourth grade. Those results have to be carefully interpreted according to sample sizes, small effect sizes, and low power. By taking these into account, we consider medium to be irrelevant for capturing procedural and structural system thinking because of comparable correlations arguing for the adequacy of both media. With respect to the influence of directedness on the validity of the CM task, we can clearly set priorities on the highly directed practice in both the fourth and eighth grades and for both procedural and structural system thinking. To summarize, we consider highly directed computer based practices to be appropriate for system thinking measurement, particularly for fourth graders, who obviously benefit from support by providing concepts and linking words that draw students' attentions more intensively toward the underlying system and facilitate the demand for conceptual knowledge.

As science education deals with a variety of complex systems, it stands in need of adequate approaches for students to acquire system thinking. Due to the fact that the development of system thinking assessment instruments is still not methodologically sound (Jacobson & Wilensky, 2006), there is a need for appropriate assessment instruments for educational researchers as well as for educators (Plate, 2010). In the case of elementary student assessments, such instruments need to supply an easy understanding and handling possibly combined with facilitative large-scale usage. Alternative tasks, for example, interviews or classroom discussion groups, as presented by Assaraf and Orion (2010), are less practicable in the case of large-scale assessments. Highly directed concept maps are easy to deal with, even



for students of young ages, and have been empirically proven to be successful in the assessment of conceptual understanding, which is the indispensable fundamental of system thinking (Sommer & Lücken, 2010). With respect to the limitations of the study, we have to consider that the two techniques (CM and paper-pencil questionnaire) are not equivalent in their demand of verbal and reading abilities, which are important to bear in mind when aiming to assess elementary students. Although a CM instrument such as MaNET<sup>®</sup> can facilitate system thinking assessments for different grades, comparisons across different grades will be difficult anyway. As a consequence, when trying to adjust the test instruments to one of the two grades, the other one might either be under-challenged or overstrained and thereby unable to reflect the whole optional spectrum. Although we didn't observe any ceiling effects in the eighth-grade assessment, we have to admit that we abdicated the use of additional instruments, which might have provided deeper insight into the demands of the system thinking tasks, for example a reading ability task. For the reason of time restriction, it was impossible to accommodate extra testing material in addition to the questionnaire and CM tasks. Future research might overcome these limitations by offering additional tasks aimed at reading abilities or otherwise offer additional tasks independent of reading. Another important fact is that while using MaNET<sup>®</sup>, we were restricted to a highly directed computer practice because MaNET<sup>®</sup> itself wouldn't support nondirected practices. Therefore, we had to frame our system thinking assessment using an incomplete factorial design, lacking nondirected computer mapping. Despite these limitations, our results led to the conclusion that highly directed computer-based CM can be used as an appropriate tool for system thinking assessment. Computer-based CM usefully combines the

advantages of effectiveness and facilitation especially with large-group assessments of younger students.

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# **VALIDATING THE MODEL STRUCTURE OF SYSTEM THINKING**



**Abstract**

System thinking is theoretically characterized as encompassing both the structural as well as the inflective understanding of complex systems' behavior. Since it requires a wide amount of cognitive abilities, previous interpretations of the internal structure of system thinking differ substantially in the number of latent variables and thereby offer a gap to bridge by the empirical validation of system thinking's model structure. Moreover, little is known so far about the behavior of this structure in a longitudinal view or in comparison across different grades. Therefore, this study not only investigates the latent variable structure of system thinking but also was conducted to collect evidence about the construct validity concerning factorial invariance across two measurement points and 4<sup>th</sup> ( $n = 406$ ) and 8<sup>th</sup> graders ( $n = 418$ ), respectively. Regarding the hypothesized two factorial structure of system thinking the specific covariance structure was modeled in the framework of structural equation modeling (SEM), based on a biological content. As testing for measurement invariance, the consistency of the specific model structure across both measurement points and across both grades was evaluated. The results corroborate the theoretical assumption about the two-factorial model structure. Moreover, the results provide evidence for measurement invariance across both measurement points. And finally, the results reveal the same internal model structure for both the elementary and the secondary school level. The potential of this structural approach for system thinking characterization is discussed.

## 1. Introduction

System thinking as a key competence to understand the intertwined nature of complex phenomena has been a central part of science education research over the past decade focusing on students' ability to understand complex systems that are composing the social and physical environment (Jacobson & Wilensky, 2006; Lesh, 2006). Since the increasing level of complexity within heterogeneous systems like ecosystems in the field of biology (Hmelo-Silver, C. E., Surabhi, M., & Lei, L., 2007) poses immense difficulties for students' learning (e.g. Grotzer & Bel Basca, 2003), there is a great requirement to improve students' system thinking (Eilam, 2012) involving the need for a detailed analysis of system thinking to adequately contribute to students' development of this complex ability.

A complex system is described as an entity that is made up by interdependent and interacting components, that either can be physical like objects or intangible like processes, information flows, relationships, feelings, values or beliefs (Anderson & Johnson, 1997). System thinking means to understand the multilevel structure of those numerous components, their dynamic and nonlinear relationships and requires a wide amount of cognitive abilities, encompassing the structural as well as the inflective analysis of complex systemic behavior (Richmond, 1993). Exactly this system thinking provides a valuable access to the field of science, especially to the field of biology, which itself is an eminent area of intertwined systems. Thus the question of how students' system thinking can be evaluated and modeled has been in focus of some recent research in science education (e.g., Assaraf & Orion, 2010; Boersma, Waarlo, & Klaassen, 2011; Evagorou, Kostas Korfiatis, Nicolaou, & Constantinou, 2009; Hogan, 2000; Penner, 2000; Riess & Mischo, 2010; Sommer & Lücken, 2010). Assessing and evaluating system thinking consequentially involves

clarifying the model structure of system thinking. Various empirical studies have investigated system thinking, starting from elementary school (e.g. Sommer & Lücken, 2010; Assaraf & Orion, 2010) up to secondary school (e.g. Verhoeff, 2008) and university level (e.g. Jacobson & Wilensky, 2006). However, these studies differ substantially concerning the system's content in question, numbers of students and their grades. Moreover, these studies differ in their empirical interpretation of how many components system thinking does compass and consequently the assessment instruments don't inevitably assess the same components of system thinking.

To date, there is no consensus concerning the appropriate moment for the introduction of system thinking at school. Some authors emphasize the introduction of system thinking as early as possible, referring to empirical studies that provide some evidence for elementary school students being able to develop basic system thinking (e.g. Assaraf & Orion, 2010; Evagorou et al., 2009; Sommer & Lücken, 2010). Others argue that system thinking - as it is necessary to reconstruct complex systemic processes - implicates higher order thinking skills (e.g. Frank, 2000). These skills seem to be underdeveloped even at university level. Jacobson and Wilensky (2006) for example, outlined that even university students tend toward simple causal and linear explanatory statements in the context of biology rather than toward the reconstruction of complex systemic processes. Learning biology still results in expressing details and linear relations of phenomena, neglecting the macroscopic-level expression (Wilensky & Reismann, 2006). To overcome these strategies, Boersma et al. (2011) recommend the introduction of system thinking in primary school as solid base for secondary school education to improve students' basic understanding of cause-effect, form-function, and part-whole relationships corresponding to systems functional identity. Also in their article Boersma and

colleagues (2011) elaborate very precisely the strong heterogeneity of the way the concept of system thinking is described in the different studies conducted so far. Therefore the aim of our study was to elaborate and describe an empirically valid model of system thinking that can contribute to the further development of research on system thinking in science education.

## **1.2. Theoretical models of system thinking**

A theory-based empirical clarification of the structure of system thinking seems to be important to provide a solid foundation for further objective, reliable and valid assessment of system thinking. To appropriately assess system thinking means to evaluate a construct that is theoretically multidimensional, though there is no theoretical and empirical consensus about how many domains compass the ability of system thinking, yet. Consequently, different theoretical baselines of system thinking lead to different evaluation approaches that certainly generate different insights into the same ability.

Rooting in cybernetics and systems theory, the development of complex system theory has increasingly expanded over the past decades. Starting from systems theory, von Bertalanffy (1968) established a first definition of systems with (1) an organizational attribute (compassing systems identity formed by systems components) and (2) a functional attribute (resulting from interactions of the latter). Bossel (1987) amended this definition by characterizing the structure of a system as determined through relationships of systems components. Moreover, he described the structure of a system as the determining factor for systems' function and thereby accomplished the circular systemic regulation. Later on diverse studies drew a bow from such system characteristics to essential principles of system thinking, involving

the understanding of the complex dynamic, nonlinear and intertwined nature of systems that leads to the emergent multilevel system structure (Anderson and Johnson, 1997, Ossimitz, 2000, Jacobson, 2001). Furthermore, sundry groups of researchers agreed in describing system thinking as bipartite ability to (1) analyze system specific elements and their interrelationships, resulting in system specific properties, to understand cause-and effect-loops of dynamic processes and to (2) prognosticate systemic effects and consequences regarding long time development (Booth Sweeny & Sterman,2001; Kim, 1999; Maani & Maharaj, 2004). In the following, different empirical efforts appeared to model the structure of system thinking. Evagorou et al. (2009) evaluated seven domains of system thinking skills, including the comprehension of elements, spatial and temporal boundaries, subsystems as well as relationships and developmental processes. Riess & Mischo (2010) accommodate Ossimitz' (2000) structural classification with declarative knowledge (for the first three dimensions) and procedural knowledge (for the fourth dimension), leaning towards the descriptions of Frensch & Funke (1995) and Leutner & Schrettenbrunner (1989). This subdivision into two parts follows a long tradition of cognitive development research in treating knowledge as differentiated into conceptual and procedural knowledge. Conceptual knowledge here can be described as “knowledge of the concepts of a domain and their interrelations” whereas procedural knowledge is referred to as “the ability to execute action sequences to solve problems” (Schneider, Star & Rittle-Johnson, 2011; Canobi, Reeve & Pattison, 2003). Sommer & Lücken (2010) also derived a two-factorial structure from systems' theory and systems' characteristics, compassing a structural dimension (“system organization”) and a procedural dimension (“system properties”). This description relates to the model of system thinking suggested by Assaraf and Orion (2005) who

characterized system thinking as a hierarchical model in form of eight steps in the context of earth systems education. The first three steps correspond to the basic organizational framework of relationships that Sommer & Lücken (2010) later on referred to as system organization. The following five steps correspond to cyclic and dynamic processes within the system, that are responsible for system's specific properties. Determining the structure of a system, the dimension of "system organization" can be sub-categorized through "elements", "relationships" and "identity", which relates to the border of a system. The second dimension of "system properties" compasses all time and feedback-loop related processes within the system and is sub-categorized into "emergence", "dynamics" and "effects". Referring to the theoretical descriptions of Sommer and Lücken (2010), the authors align themselves with the bipartite structure of system thinking that compasses the following two parts: the structural and the procedural system thinking. Structural system thinking (SST) corresponds to identifying a system's relevant elements and their interrelationships, altogether determining the system's framework and system's identity. Procedural system thinking (PST) corresponds to the dynamic, nonlinear and complex interactions within systems' elements, that underlie time-related progresses and which can be considered to be feedback-loop-regulated. While being responsible for systems' function and development, these dynamic interactions characterize systems' integrity.

All theoretical approaches, each being supported by some empirical evidence, are unified by the assumption that the construct of system thinking is compartmented, though the number of compartments is still not clear. Moreover, none of these studies show clearly two or more empirically distinguishable compartments of system thinking. However, the distinction and interrelations between those postulated

compartments of system thinking dissociated and empirical evaluations and measurements differed in each design. Consequently, there has been no test on validating the dimensionality of system thinking, yet.

### **1.3. The challenge of validating an appropriate model of system thinking**

Since there is no empirical base concerning the number of dimensions within the construct of system thinking, there is need to provide information about the structural model and its configuration. Many studies refer to a two-compartmented structure. But in the same time they all document a very close relationship between both dimensions. It is well documented that the ability to understand and recapitulate processes systemically goes along with the knowledge about the systemic structure. Moreover, the understanding of system's elements and their relationships considerably facilitates the approach to systems' processes and development. Consequently, both dimension influence and probably regulate each other to a degree that is significantly important for the structure of system thinking. Such reciprocal dependency might also influence the empirical modeling of the construct. A model with two dimensions of system thinking can only be postulated, if there is empirical evidence that cannot be interpreted better by a one-factor-model. Therefore it is essential to compare the model fits of a two-factorial model structure with those of a one-factorial model structure. Nevertheless, though a two-dimensioned model seems theoretically likely, one may rest assured that there are high correlations between both dimensions.

#### 1.4. Aims of the study

Linking to the variety of structure models described above we hypothesized the construct of system thinking as two-dimensional, encompassing a structural and a procedural factor. Moreover, we act on the theoretical assumption that the dimension of structural system thinking is closely associated with the dimension of procedural system thinking. This interlacement plays an important empirical role concerning the clear division of two dimensions. Thus, we're aiming on clearing (1) the internal structure of the construct, (2) the structure consistency through two measurement points and (3) the structure consistency through different grades. So the first question, whether these two theoretical dimensions can be evidenced, is to be made out: "Can we empirically approve the theoretical assumption of a two-factorial structure of system thinking?" Concerning the fidelity of the factorial structure throughout more two measurement points, we pose the second question: "Is the empirically modeled structure of system thinking invariant at both measurement points?" And relating to the measurement invariance across different grade we pose the third question: "Is the empirically modeled structure of system thinking invariant across two different grades?" If the latent factor structure of system thinking is two-dimensional as hypothesized, a two-dimensional model should fit better than a single factor model. If both measurement points assess the same underlying construct of system thinking, we should find the same construct structure at each measurement point. In case of validating the underlying construct across different groups, it is indispensable to assure the same theoretical structure for both groups (see Dimitrov, 2010). Both testing for factorial invariance across different measurement points and across different groups is yet not applied regarding the construct of system thinking. We therefore conducted the following study to test for factorial invariance among two



measurement points and among 4<sup>th</sup> and 8<sup>th</sup> graders, respectively. We used a test for system thinking (Brandstädter, Harms & Großschedl, 2012) in a longitudinal design at two measurement points and posed the following hypotheses:

1. The two-dimensional model of system thinking fits the data better than a one-factor model.
2. The two-dimensional model of system thinking is invariant during different measurement points.
3. The two-dimensional model of system thinking is invariant across different grades.

## **2. Methods**

### **2.1. Sample**

Twenty one fourth-grade science classes from 15 German primary schools and 15 eighth-grade biology classes from 8 German secondary schools participated in the study. Secondary schools were both Academic track and non-academic track schools. Fourth graders ( $n = 406$ ) were 9 to 11 years old (mean age: 9.83 years;  $SD = 0.35$ ). Eighth graders ( $n = 418$ ) were between 13 and 15 years of age (mean age: 14.01 years;  $SD = 0.57$ ). Gender was distributed evenly in the fourth and eighth grades: 47.9% of fourth graders and 49.8% of eighth graders were female.

### **2.2. Procedure**

The study was part of an extensive experimental evaluation project concerning the structure and development of system thinking. The participants were tested in their regular classrooms at two measurement points (T1 and T2). The pretest and posttest consisted of a SST/PST questionnaire, which was exactly the same for both

grades. The biological system used for the study was the blue mussel in the ecosystem Wadden Sea. Prior to this study, the material was pretested in nine 4<sup>th</sup> and seven 8<sup>th</sup> classes to serve adequate and comparable teaching and instruction material. As a result, teachers got detailed to-the-minute information for each lesson to provide exactly the same lesson and instruction procedure for each class at both grades. Moreover, teachers were requested to adhere to teaching material, and they were directed to report whether and in which way they deviated from the teaching material. Based on teachers' reports, we concluded that teachers closely adhered to the teaching material and their deviations were minimal. All students took part voluntarily in the study.

### **2.3. Operationalization of dependent variables SST and PST**

A system thinking test was applied to assess structural and procedural system thinking. The SST questionnaire contained eight items (see App. A), six multiple choice items and two open ended items. The scale of SST items focused on the basic structure of the "blue mussel ecosystem", concerning the relevant system elements, their functions and relationships. The PST questionnaire contained five items, three of them were closed and two were open. The scale of PST items (see App. A) aimed at the development of certain processes within the system. Aiming on the assessment of both structural and procedural system thinking, we avoided to provide knowledge about each functional chain within the system. For that, it is important to note that the process interactions, assessed within the PST scale, were not part of the intervention unit. Those lessons served as knowledge provider but explicitly not as provider of procedural system knowledge. Consequently, the PST items were prompting for something which wasn't presented in the lessons before

and therefore had to be developed. The multiple choice items differed in their numbers of answers just as in their numbers of points. To obtain a consistent metric item design, the items were categorized afterwards to a categorical level evaluation score of 0, 1 and 2 points. The open items were evaluated in the same way (0 = the answer was incorrect, 1 = the answer was partly correct, or correct but the reasoning was lacking, 2 = the answer and corresponding reasoning was correct). To determine the rater agreement, inter-rater reliabilities were computed for open questions in both scales SST and PST. 15% of the items were scored by two raters. Raters' individual proposition scores were compared by calculating unadjusted intra-class correlations. Intra-class correlation coefficients (ICCs) were substantial for all conditions. (SST: ICC= 0.862; PST: 0.882).

To analyze the covariance structure of our data, we used the MPlus program (Muthén & Muthén, 1998-2007). We used confirmatory factor analysis (CFA) in the context of structural equation modeling (SEM) to ascertain the degree to which the scoring structure fits to the hypothesized theoretical structure of system thinking. Regarding the first research question, we were testing for different model fits relating to different model structure of system thinking at one measurement point. A comparative fit index (CFI) above .95, a Tucker Lewis index above .95, and a root mean square error of approximation (RMSEA) below 0.05 indicate a good fit (Hu & Bentler, 1999). Regarding the second research question, we were testing for factorial invariance across two measurement points. Regarding the third research question, we were testing for factorial invariance across 4<sup>th</sup> and 8<sup>th</sup> grade at two measurement points.

For configural invariance, all parameters were allowed to vary freely between occasions. For metric invariance the factor loadings were constrained to be equal and for scalar invariance, item thresholds were fixed.

Table 1 shows the internal consistencies of the accuracy scores in the form of cronbach's  $\alpha$ . By focusing on comparison between groups, most of the coefficients indicated sufficient consistencies (Lienert & Raatz, 1994). The coefficient for PST in at the pretest measurement displays slightly insufficient consistence.

**Table 1:** Internal consistencies for SST and PST

	cronbach's $\alpha$	
	pretest	posttest
SST	.52	.50
PST	.44	.59

### 3. Results

#### 3.1. Construct structure

First of all we specified for the pretest measures a one factor model and a two factor model to test for the first research question. Additionally we tested for a nested factor model in case that the hypothesized high correlations between both dimension in the two-factorial structure might be better reflected by a nested factor model, that is based upon a common underlying factor of both latent variables. The fit indices in Table 2 for the one-factor model indicate almost the same fit indices as for the two-factor model, the fit indices for the nested factor model were far beyond the acceptable frame of model fits. This is due to the high inter-correlations of the two

latent factors in the two-factor model. The correlations between SST and PST were 0.963 at pretest measurement and 0.831 at posttest measurement.

In detail, the fit indices for the one-factor model are slightly better than for the two-factor model at pretest measurement. This changed at posttest measurement where the two-factor model indices slightly outperform those of the one-factor model.

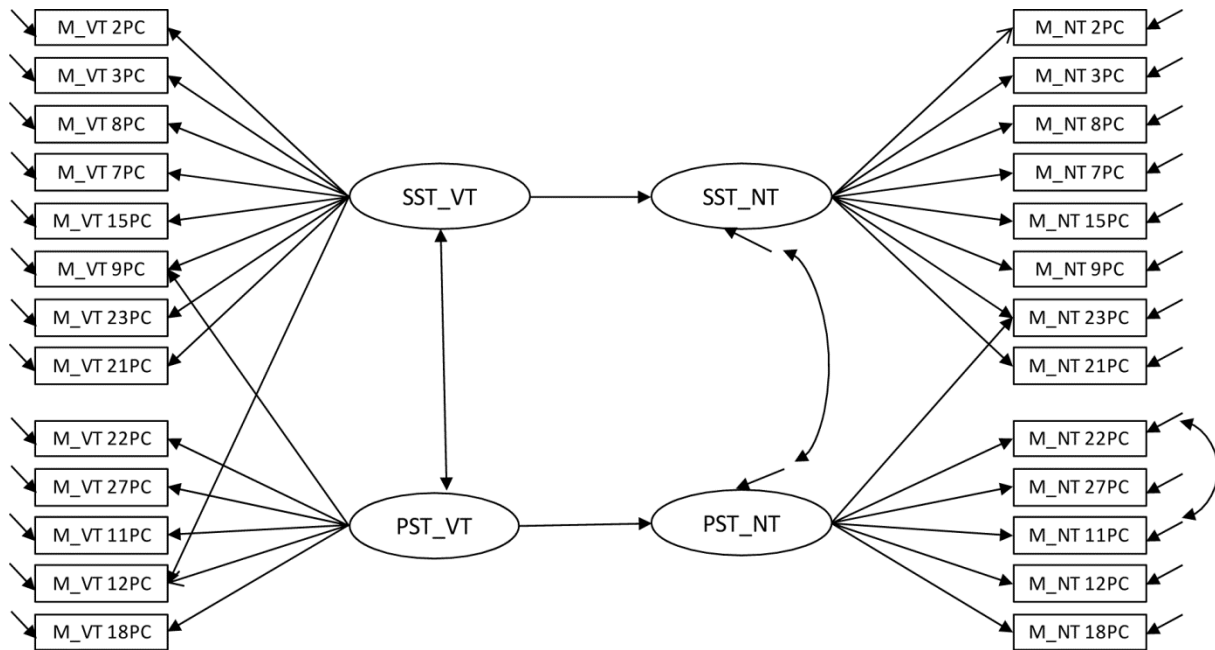
**Table 2:** Fit indices for one and two factor models

		$\chi^2$	<i>df</i>	<i>p</i>	CFI	TLI	RMSEA
pretest	two factors	86.446*	64	0.0323	.932	.917	.040
	one factor	86.807*	65	0.0367	.934	.920	.039
	nested factor	87.025*	55	0.0038	.902	.862	.052
posttest	two factors	89.401*	64	0.0197	.932	.917	.051
	one factor	93.430*	65	0.0120	.924	.909	.054

### 3.2. Invariance analysis

To test for the internal model structure over two measurement points, we tested the model fits relating to factorial invariance. To test for factorial invariance in this case means to test for one group across different points of time. Testing for factorial invariance addresses testing for three steps of invariance: *configural invariance*, *measurement invariance* and *structural invariance* of the model (e.g. Dimitrov, 2010, Byrne, 2004; Cheung & Rensvold, 2002).

As a first step we were testing for configural invariance. We specified our baseline model for both measurement points (Figure 1), allowing two items at pretest measurement to predict both latent variables. At posttest measurement, we allow one item to predict both latent variables, additionally, we allow a correlation between two items of the PST\_NT scale. All these assumption were made for content reasons.



**Figure 1:** Measurement model of system thinking with two latent variables

Referring to our baseline model, we then were testing for measurement invariance in the steps of metric invariance (weak measurement invariance) and scalar invariance (strong measurement invariance). For configural invariance measurement we set no constraints concerning factor loading and item thresholds. With configural invariance in place (Table 3) we constrained for metric invariance the factor loadings to be equal across the two measurement points (Table 3). With metric invariance in place, we then constrained item thresholds to be equal across the two measurement points. The model fits for scalar measurement invariance indicated no perfect invariance across thresholds, but neither showed evidence for complete inequality. Consequently, we set some thresholds free (non invariant) across the two measurement points to gain partial scalar invariance (Table 3). Since less than 20 % freed parameters is acceptable in practical applications (Byrne et al, 1989; Levine et al, 2003), we decided, depending on the reported modification indices, to free the thresholds of item 8, 11 and 18.

**Table 3:** Model fits for configural, metric and partial scalar invariance

invariance	<i>df</i>	<i>p</i>	CFI	TLI	RMSEA
configural	278	.0026	.936	.925	.040
metric	288	0.019	.953	.946	.034
scalar, partial	292	0.023	.955	.950	.033

Note *CFI* = comparative fit index; *TLI* = Tucker Lewis index; *RMSEA* = root mean square error of approximation

Both the strong measurement invariance model fits and the metric measurement invariance model showed good model fit indices, except for the TLI, that differed slightly from optimum. The fit indices for the configural model indicate slightly nonoptimal but still acceptable fit indices.

### 3.3. Invariance through different grades

Manifest measurements in form of means and standard deviations of pretest and posttest in both grades were given in Table 4.

**Table 4:** Means and standard deviations at pre- and posttest measurement of SST and PST in 4<sup>th</sup> and 8<sup>th</sup> grade

		pretest		posttest	
		<i>M</i>	SD	<i>M</i>	SD
4th grade	<b>SST</b>	0,644	0,304	1,009	0,261
	<b>PST</b>	0,598	0,442	1,089	0,439
8th grade	<b>SST</b>	0,950	0,278	1,136	0,249
	<b>PST</b>	0,924	0,292	1,270	0,395

Results show increasing SST and PST scores in both grades at both measurement points. All SST and PST measures were significantly higher at the posttest when compared to pretest SST and PST measures in both grades.

Moreover, 8th graders showed significantly higher SST and PST scores than 4th graders, both at pre- and at posttest.

Referring to the baseline model that we tested in 4<sup>th</sup> grade, we wanted to know if we can provide evidence for the same construct structure at the same measurement points in 8<sup>th</sup> grade. Consequently, we specified the model structure while modeling measurement invariance across groups for both measurement points. For the configural invariance measurement we specified the reference model of 4<sup>th</sup> grade with free factor loadings, free item thresholds and fixed the factor mean to zero and the factor variance to one to enable identification. In the alternative model of the 8<sup>th</sup> grade we as well as in the reference group set the factor loadings and item thresholds free and fixed the factor mean to zero and the factor variance to one. For the metric invariance measurement, we specified the factor metrics by setting the factor loadings equal across both groups and additionally fixed the factor mean to zero to enable model identification. For the scalar invariance measurement we still hold the factor loadings equal and additionally set the item thresholds equal across both groups. Factor mean and variance were then set free in the alternative group of 8<sup>th</sup> grade. Table 5 and 6 show the multigroup analysis results for both measurement points. Regarding the pretest measurement, the model fits show good fit indices whereas the fit indices regarding the posttest didn't achieve acceptable quality. Assuming that these fits could have been a sign of a better fitting one factor model at posttest, because of a higher level of content knowledge that possibly could have led to a two-factor-fusion, we again tested the one factor model. The one factor model fits by far felt off in quality and thereby didn't confirm this assumption.



**Table 5:** Model fits for multigroup analysis concerning configural, metric and scalar invariance at pretest measurement

VT	$\chi^2$	<i>df</i>	<i>p</i>	CFI	TLI	RMSEA
group config	160.948*	135	0.0633	0.950	0.942	0.031
group metric	158.460*	133	0.0653	0.951	0.942	0.031
group scalar	169.623*	144	0.0711	0.950	0.946	0.029

**Table 6:** Model fits for multigroup analysis concerning configural, metric and scalar invariance at posttest measurement

NT	$\chi^2$	<i>df</i>	<i>p</i>	CFI	TLI	RMSEA
group config	158.912*	132	0.0553	0.942	0.931	0.040
group metric	193.434*	145	0.0044	0.895	0.887	0.051
group scalar	235.375*	156	0.0000	0.828	0.828	0.063

#### 4. Discussion

With this study we want to put up for discussion an empirically tested model to supplement the different models described above. Since the further investigation on internal relations and development of system thinking is a difficult task before clarifying the structure of system thinking, we made efforts to collect evidence about specific aspects of construct validity (Messick, 1995). We first evaluated the specific scoring structure on the basis of CFA with respect to the hypothesized two factorial structure of system thinking. As then testing for factorial invariance in the framework of SEM, we evaluated the consistency of the specific model structure throughout two measurement points. Factorial invariance in this case includes measurement invariance, referring to configural, metric and scalar invariance (see Dimitrov, 2010). Regarding the first research question, we can corroborate the theoretical assumption about the two-factorial model structure rather than the one-factorial model structure. Although the one-factorial model fits the data slightly better at pretest measurement, we nevertheless obtained a better fitting two-factorial model at posttest

measurement. We consider this as being rooted in the factual knowledge input during intervention. For the reason that the content of the intervention unit was usually not part of the curriculum, the factual knowledge was not extensively present at pretest measurement. As Sommer & Lücken (2010) state, the corresponding factual knowledge is a fundamental precondition to think systemically, one can assume that the splitting into two factors is observable not at the beginning but in the end of intervention. However, concerning the limitations of the study, the reliabilities of both scales were not satisfying. For this case, one has to keep in mind that Cronbach's alpha is sensitive to sample size and to the number of items. Both sample size and number of items in both scales were at the minimum but did not reach optimal sizes. With respect to the students' age at elementary school, it is entirely conceivable that requirements to answer the questions compass also reading or text literacy that may have varied from one item to another. These findings go along with those of Riess and Mischo (2010) who in turn tied in with the PISA-studies sub-optimal homogeneities concerning the scale for competence of problem solving. This might indicate an investigation for future research to methodically complement additional tasks, for example reading literacy that facilitates to selectively separate the scales. Nevertheless, the correlation between both factors is still high at posttest measurement. We therefore assume close relations between both factors and future research might show how these relations function in detail. The high correlations might also lead to the assumption that there might be a common underlying factor, such as content knowledge. This assumption could have been supported, if a nested factor model would have been generated better model fits than the two-factor-model did. The results indeed display a two-factorial structure, but still with high correlations among both factors. Assuming that the understanding of complex systems is

attended by enormous working memory resources (Feltovich, Coulson & Spiro, 2001) and immense general cognitive challenges (Jacobson & Wilensky, 2006), explanations for correlations within the structure of system thinking, especially for the tight relations of both factors can possibly be found in the field of cognitive development. Already Leutner and Schrettenbrunner (1989) described two independent aspects of system thinking, namely systems-oriented thinking and controlling action that were referred to as declarative and procedural knowledge (Riess & Mischo, 2010). Cognitive development researchers have tried to examine the central questions about how these both kinds of knowledge influence each other (e.g. Dixon & Moore, 1996; Schneider & Stern, 2010; Rittle-Johnson, Siegler & Alibali, 2001). From the theoretical point of view, four different types of interrelations of conceptual and procedural knowledge are described, each underlined with some empirical evidence (Schneider, Rittle-Johnson & Star, 2011): The *concepts first theories* indicate that children acquire first conceptual knowledge which then serves as base for the development of procedural knowledge (e.g. Gelman & Williams, 1998). The *procedures first theories* indicate the opposite; children first acquire procedures and then start to build conceptual knowledge (Siegler & Stern, 1998). The *inactivation view* describes both components of knowledge as mutually independent (Resnick & Omanson, 1987). The fourth theory of the *iterative model* allows for the possibility that both concepts first and procedures first theories serve a plausible base to describe the relationship between conceptual and procedural knowledge (Rittle-Johnson, Siegler & Alibali, 2001). Recently, Schneider, Rittle-Johnson & Star (2011) provided empirical evidence that supports the iterative model of knowledge development. After evaluating the relations between both kinds of knowledge over time, they assessed significant bidirectional relations that are almost

symmetrical. It therefore follows that both kinds of knowledge account for each other. Thus, developing one kind of knowledge in practicing or learning processes helps growing the other one (Schneider, Rittle-Johnson & Star, 2011). This might also be a plausible reason for the tight connection between both dimensions of system thinking. The structuring of new acquired systems' content knowledge may lead to suitable understanding of system processes, time related development within the system and feedback-loop thinking. In turn, experiencing system related processes might strengthen the understanding of systems' structure, elements and concept functioning. Future research is needed to clarify those specific and longitudinal relations between structural and procedural system thinking. Our design with the same assessment tasks at pre- and posttest measurement allowed us to test whether our system thinking tasks functioned with the same pattern of latent variables across different measurement points. We could provide evidence for the two-factorial structure pattern across both measurement points. But one aspect that changed over time was the correlation between both latent variables. Our findings concerning the lower correlation factor at posttest measurement did not meet the results from Schneider et al. (2011) who recognized an increasing correlation factor between both knowledge fragments of conceptual and procedural knowledge and posttest measurement. But since there is evidence that the tying of different knowledge fragments that leads into the understanding of processes and concepts is considerably harder with low domain expertise than the integration of knowledge fragments with higher domain expertise (Linn, 2006; Schneider & Stern, 2009), we trace the higher correlation at pretest measurement back to the lacking domain knowledge. Additionally, the incorporation of general system knowledge in the intervention unit possibly may facilitate the structuring and understanding of the new

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content knowledge fragments. In the present study, we consciously abdicated a specific unit about general system knowledge. As Hmelo-Silver and Azevedo (2006) recommended “scaffolding” students’ system thinking when they are expected to think systemically thinking systemically, possibly a combination of content knowledge and general system knowledge within the intervention unit would sharpen a more precise model structure. These suggestions are in line of those with Yoon (2008), who used the educational system itself as point of system reference to understand global phenomena systemically.

Until now in the area of system thinking research, we could benefit from studies that theoretically investigated the structure of system thinking and provided some empirical evidence with assessment instruments that were not evaluated to resist rigorous validating processes, for example invariance analysis as common psychometric method for structural validation (Dimitrow, 2010). In the current study a structural equation modeling approach helped us to investigate the two factorial latent variable structure of system thinking not only for the elementary level but also for secondary school level. Therefore, we not only can support the theoretical assumptions from former studies that assumed the multidimensional structure of system thinking already at elementary school (Brandstädter et al., 2012., Evagorou et al, 2009, Sommer & Lücken, 2010 ), but also we can draw a bow on the invariant model structure over time when the specified model compasses the results from 8<sup>th</sup> graders. This construct stability provides fundamental information about the development of system thinking. The construct structure of system thinking here appears as stable throughout two measurement points and didn’t turn into a one-factor structure even after an immense knowledge input across the intervention unit. Obviously, the two-factorial pattern didn’t melt into one big factor of content

knowledge at posttest measurement. This fact actually displays that new acquired knowledge, though being indeed an indispensable part of system thinking, can be added to without superposing the two-factorial pattern system thinking as one big factor. Our results do not only count for the patterns of structural and procedural system thinking but also for kinds of knowledge in general. Until now there is no connection between studies about system thinking and studies about the development of cognitive abilities or the development of knowledge in general. Such combined investigations would enlighten future system thinking research, because they should provide implications for not only the understanding of system thinking development but also for the development of other cognitive abilities like problem solving competence for example (Hmelo-Silver & Azevedo, 2006).

#### **4.1. Limitations**

The authors acknowledge a number of limitations. A complex evaluation project of system thinking framed this study and provided the opportunity to evaluate the structure of system thinking. Such an involvement is connoted with the adaption of the content, in this case the “blue mussel”, a local basis in form of a biological system. Therefore, the aspect of generalizability has to be carefully considered. Also concerning generalizability, the study’s conclusions have to be restricted with respect to the two different stages of development, namely 4<sup>th</sup> and 8<sup>th</sup> grade. The wording and the requirements of the evaluation instruments would have been provoked ceiling or floor effects at lower or higher grades. Another limitation is the number of measurement points that indeed offer the possibility to specify the structure of system thinking over time. But the addition of more measurement point surely would lead to more precise information about the development of system thinking over time.

Additionally, a supplementation of systemic metaknowledge during intervention might result in a more detailed picture of not only the factors but also the relations in between the complex ability of system thinking. Investigations like this should provide effective possibilities to enhance the teaching and learning of science. Consequently, the understanding of how we learn to think systemically also provides valuable information about how we think and learn in general. Moreover, further studies are needed to precisely determine the development of system thinking across more different age levels and in more diverse content areas. This would contribute to the ongoing discussion about whether system thinking is domain specific or not.

Since we are still far from understanding about how the development of system thinking is influenced by various contents or age levels and about how other areas of cognitive skills and system thinking are related to each other, our results provide sound empirical preconditions to efficiently investigate such questions in future research.

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**CHARACTERIZATION OF SYSTEM THINKING: RELATIONS  
AMONG STRUCTURAL AND PROCEDURAL SYSTEM  
THINKING IN 4<sup>TH</sup> AND 8<sup>TH</sup> GRADE**

**Abstract**

System thinking development affects both the structural as well as the inflective understanding of complex systems' behavior. However, though being characterized as two-factorial construct, former investigations of system thinking revealed a close connection in form of a high correlation between structural and procedural system thinking. Thus, questions arose concerning the development of each aspect of system thinking. A "bottom up" development regarding the acquirement of new content knowledge advancing a structural system understanding as fundament for procedural system thinking is contrasting the "top down" influence of understanding system related processes facilitating the understanding of systems' structure. Since, suggesting older students' to revert to a higher level of cognitive abilities, the influencing effects of general cognitive abilities are put in the focus here, comparing 4<sup>th</sup> ( $n = 406$ ) and 8<sup>th</sup> graders( $n=418$ ), across two measurement points, respectively.

Thus, pointing to the need to get a deeper insight of the internal structural pattern of system thinking while focusing on age-dependent effects, the relationships between structural and procedural system thinking were modeled in the context of a biological ecosystem unit as manifest factors to test: (1) Which general level of structural and procedural system thinking do elementary students achieve in comparison to secondary students (2) Whether the predictive relations between structural and procedural system thinking were bidirectional both in 4<sup>th</sup> and 8<sup>th</sup> grade and (3) How the internal structure pattern of system thinking contribute to general cognitive abilities both in 4<sup>th</sup> and 8<sup>th</sup> grade. Result show that both grades improved differently their system thinking skills. Though the gain of structural system thinking was approximately equal in both grades, 4<sup>th</sup> graders gain of procedural system

thinking, was significantly higher than in grade 8. The results provide valuable information concerning the question to which extent elementary students are able to convey system thinking perceptions. 4<sup>th</sup> graders succeeded more effectively in generating relationships and developmental processes from a structural fundament. In turn, 8<sup>th</sup> graders concentrated evenly on structural and procedural system thinking. Additionally, results confirm the hypothesized bidirectional structural pattern of system thinking in both grades, being supported but not modified by general cognitive abilities. Finally, the results clearly point to investigations in further research to clarify processes supporting the emergence of initial structural system thinking improving procedural system thinking and vice versa.



## 1. Introduction

In the context of an ecosystem unit a group of elementary students was invited to prepare a role play to simulate two characters - "blue mussel" and "oyster" - of the Wadden Sea ecosystem. They began with collecting some general facts. Both of the mussels bear the same live style, being attached sessile, sharing the same intertidal biotope, they don't feed each other, they don't attack each other. As filter feeders, both are playing an important role in estuaries. Looking through the presented material, the student's attention is suddenly focused on an article that demonstrates the dramatic impact of oysters on not only blue mussels but also on eider ducks, common shore crabs and not least on humans. "How does that come?" The students asked. "Why are such immobile little oysters that dangerous for blue mussels?" This perplexity concerning a complex systems' multilevel structure arises not solely in biological systems, but also in complex social and environmental systems that declare nonlinear behavior. Especially the intertwined nature of ecosystems poses immense difficulties for students understanding (Reiner & Eilam, 2001; Hmelo-Silver et al., 2007). These difficulties are not only due to the complex multilevel structure of ecosystems (Grotzer & Bel Basca, 2003), but also to students' prior knowledge and general cognitive abilities, that even well-educated individuals don't develop adequately concerning the comprehension of complex systems' behavior (Booth Sweeney & Sterman, 2000). A complex system is described as an entity that is made up by interdependent and interacting components, that either can be physical like objects or intangible like processes, information flows, relationships, feelings, values or beliefs (Anderson & Johnson, 1997). Due to the hierarchical multilevel nature, the aggregate emergence of a complex system is not predictable from individual system elements, but arises as macroscopic level interaction, resulting from the interaction of

those elements on the microscopic level (Hmelo-Silver & Pfeffer, 2004). System thinking as ability to understand the multilevel structure of those numerous components, their dynamic and nonlinear relationships requires a wide amount of cognitive abilities. Therefore, it compasses the structural as well as the inflective analysis of complex systemic behavior (Richmond, 1993). Since the understanding of complex systems is accompanied with grounding principles, it provides a fundamental connection between numerous science domains (Goldstone & Wilensky, 2008). System thinking supports a valuable access to the field of science, especially to the field of biology, which itself is an eminent area of intertwined systems. This perception of system thinking's importance for science education in biology (e.g. Assaraf & Orion, 2010; Brandstädter, Harms & Großschedl, 2012; Sommer & Lücken, 2010; Verhoeff, Waarlo, & Boersma, 2008) is attended by need for educational support to help students develop system thinking. Since now students' biology learning and understanding is often rather compartmented and deficit, confronting them with serious challenges concerning the systemic processes changing in time (Jacobson & Wilensky, 2006; Wilensky & Reisman, 2006). As a result, the backlog demand of system thinking supportive education one the one hand refers to comprehension problems of biological systems that even experienced teachers revealed in diverse studies (e.g. Penner, 2000) and on the other hand to the transmission of advantages of system thinking oriented education to the multiplying audience of educators (Plate, 2010). To overcome these deficits one aim is to mediate general principles rather than the transmission of facts and static details to support the understanding of the macroscopic system behavior (Hmelo-Silver, Marathe & Liu, 2007). Having this agenda, it is indispensable to characterize the structure and developmental properties of system thinking. Since Brandstädter &

Harms, [in prep.](#)) described the latent variable structure of system thinking as two-dimensional, there is need to investigate the internal relationship and development of each aspect of system thinking. A “bottom up” relationship concerning the acquirement of new content knowledge supporting a structural system understanding as fundament for procedural system thinking is contrasting the “top down” influence of understanding system related processes facilitating the understanding of systems’ structure. A bidirectional relationship would support the theoretical assumption of an iterative model structure.

Another focus of current system thinking research is to develop new science curricula containing instructional support concerning basic system principles (Jacobson & Wilensky, 2006; Assaraf & Orion, 2005). However, despite the consensus about the integration of system based instructional modes to promote system thinking as meaningful approach for various scientific disciplines, there is no consensus about the appropriate moment for the introduction of system thinking at school. Diverse studies argue that system thinking - as it is necessary to reconstruct complex systemic processes - involves higher order thinking skills (e.g. Frank, 2000) that seem to be challenging for even university students (Jacobson & Wilensky, 2006) who tend toward simple causal and linear statements in the context of biology rather than toward the reconstruction of complex systemic processes. Others recommend the introduction of system thinking as early as possible, referring to empirical evidence for elementary school students being able to develop basic system thinking (e.g. Assaraf & Orion, 2010; Brandstädter, Harms, & Großschedl, [2012](#); Evagorou, Kostas Korfiatis, Nicolaou, & Constantinou, 2009; Sommer & Lücken, 2010). To answer the question of whether or not and to which level system thinking could be transmitted in to students of different developmental stages, the

influence of general cognitive abilities are put in the second focus here, comparing 4<sup>th</sup> ( $n = 406$ ) and 8<sup>th</sup> graders ( $n = 418$ ), across two measurement points, respectively. The internal relationships of system thinking, including age-dependent effects were modeled in the context of a biological ecosystem unit.

### **1.1. The structure of system thinking**

Understanding the process of students' system thinking development as one of the current interests in science education research is intrinsically tied with the understanding of the internal structure of system thinking. Rooting in cybernetics and systems theory, the development of complex system theory (von Bertalanffy, 1968; Bossel, 1987) served as initial point for diverse studies that theoretically drew a bow from complex system characteristics to essential principles of system thinking (Anderson and Johnson, 1997, Ossimitz, 2000, Jacobson, 2001). Thereby, particularly the emergent and multilevel behavior of a complex system was assumed to be essential for the understanding of the dynamic, nonlinear and intertwined system structure. Referring to Frensch & Funke (1995) and Leutner & Schrettenbrunner (1989), Riess & Mischo (2010) summarize Ossimitz' (2000) fourth dimensional classification of system thinking by combining the first three dimensions (1: network thinking, 2: dynamic thinking, 3: thinking in models) as declarative knowledge and the fourth dimension (4: system-compatible action) as procedural knowledge. Treating knowledge as differentiated into conceptual and procedural knowledge follows a long tradition of cognitive development research. Conceptual knowledge here can be described as "knowledge of the concepts of a domain and their interrelations" whereas procedural knowledge is referred to as "the ability to execute action sequences to solve problems" (Schneider, Rittle-Johnson & Star,

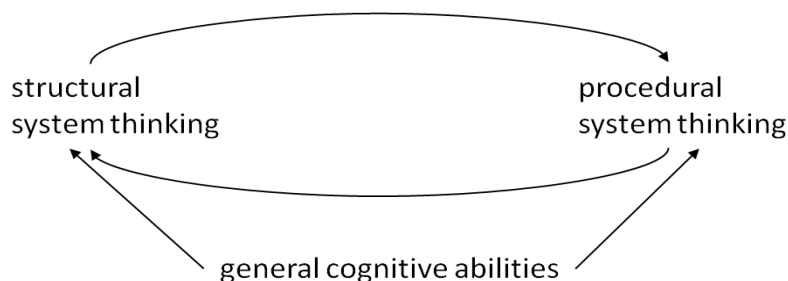
2011; Canobi, Reeve & Pattison, 2003). Sommer & Lücken (2010) also derived a two-dimensional structure from systems' theory and characteristics, encompassing a structural dimension ("system organization") and a procedural dimension ("system properties"). Referring to the theoretical framework of Sommer and Lücken (2010), Brandstädter, Harms & Großschedl (2012) described system thinking structural and procedural understanding of a system. Structural system thinking is the ability to identify a system's relevant elements and their interrelationships, altogether determining the system's framework. It refers to the ability to define the relevant elements that structurally characterize a system and to be able to distinguish the relevant system from other surrounding systems precisely. Procedural system thinking is referred to as ability to understand the dynamic and time-related processes that emerge from the systems' structure, particularly occurring in within systems' interacting elements, and subsystems. These can be considered as microscopic level that is causally linked with the superior macroscopic level of complex system properties often occurring simultaneously and with indirect causality (Serman, 2008). Regarding the structural characterization of system thinking, Brandstädter & Harms, *in prep.*) investigated the latent variable structure of system thinking and provided empirical evidence for a two-dimensional model structure. Moreover, the latent construct structure proofed to be invariant across different measurement points and across different classes (4<sup>th</sup> and 8<sup>th</sup> grade). Though there is the general assumption of a close relation between structural and procedural system thinking (Assaraf & Orion, 2010; Sommer & Lücken, 2010; Brandstädter & Harms, *in prep.*), little is known so far about the precise relation of these two dimensions.

## 1.2. Relations between structural and procedural system thinking

Cognitive development researchers have tried to examine the central questions about how conceptual and procedural knowledge influence each other (e.g. Dixon & Moore, 1996; Schneider & Stern, 2010; Rittle-Johnson, Siegler & Alibali, 2001). From the theoretical base, four different types of interrelations of conceptual and procedural knowledge are described, each underlined with some empirical evidence (Schneider, Rittle-Johnson & Star, 2011): The *concepts first theories* indicate that children acquire first conceptual knowledge which then serves as base for the development of procedural knowledge (e.g. Gelman & Williams, 1998). The *procedures first theories* indicate the opposite; children first acquire procedures and then start to build conceptual knowledge (Siegler & Stern, 1998). The *inactivation view* describes both components of knowledge as mutually independent (Resnick & Omanson, 1987). The fourth theory of the *iterative model* allows for the possibility that both concepts first and procedures first theories serve a plausible base to describe the relationship between conceptual and procedural knowledge (Rittle-Johnson, Siegler & Alibali, 2001). Recently, Schneider, Rittle-Johnson & Star (2011) provided empirical evidence that supports the iterative model of knowledge development. After evaluating the relations between both kinds of knowledge over time, they assessed significant bidirectional relations that are almost symmetrical. It therefore follows that both kinds of knowledge account for each other. Thus, developing one kind of knowledge in practicing or learning processes helps growing the other one (Schneider, Rittle-Johnson & Star, 2011). This might also be a plausible reason for the tight connection between both dimensions of system thinking. Form a “bottom up” point of view, the structuring of new acquired systems’ content knowledge may lead to suitable understanding of system processes, time

related development within the system and feedback-loop thinking. In turn, experiencing system related processes might as a “top down” influence strengthen the understanding of systems’ structure, elements and concept functioning. Thus, current questions arose from these underlying assumptions: When students activate their system thinking while being concerned with a complex biological system, does knowledge about systems’ elements, their relations and organizational framework contribute to the development of structural system thinking as well as to the development of procedural system thinking? Moreover, one might assume that older students, reverting to a higher level of cognitive abilities that Frank (2000) requires to develop an adequate understanding of systems’ macroscopic behavior could profit from their procedural system thinking more efficiently concerning the understanding of both microscopic and macroscopic level. On the other hand, it might be conceivable that younger students’ system thinking development is primary influenced by their structural understanding of complex systems, that possibly plays a bigger role regarding to the development of structural system thinking than to the development of procedural system thinking. Therefore, another question that addresses the internal relations of system thinking is: Are there differences concerning these relations between structural and procedural system thinking with respect to different grades? Additionally, it might be interesting, how general cognitive abilities contribute to both structural and procedural system thinking at each grade. Hypothesizing an iterative model structure of system thinking (Fig. 1), the aims of the current study were threefold the aims of the current study were threefold: 1) To test for differences between 4<sup>th</sup> and 8<sup>th</sup> grade students concerning the general level of structural and procedural system thinking 2) to test whether the predictive relations between structural and procedural system thinking are bidirectional concerning both

in 4<sup>th</sup> and 8<sup>th</sup> and 3) to evaluate how the internal structure pattern of system thinking in both grades contribute to general cognitive abilities.



**Figure1:** Iterative model of system thinking development

## 2. Procedure

The study was part of an extensive experimental evaluation project concerning the structure and development of system thinking.

The biological system used for the study ‘blue mussel’ in the ecosystem Wadden Sea was chosen in order to serve an intervention unit that is not obligatorily part of the curriculum but comprises a high relevance regarding the local situation in Schleswig Holstein that is framed by the Wadden Sea at the western coast side of Germany. Therefore, it was possible to provide each classroom with ‘living material’. For that purpose, teachers had to use an aquarium and teaching material that was provided by the instructor. Prior to this study, the material was pretested in nine 4<sup>th</sup> and seven 8<sup>th</sup> classes to serve adequate and comparable teaching and instruction material. As a result, teachers got detailed to-the-minute information for each lesson to provide exactly the same lesson and instruction procedure for each class at both grades. Moreover, teachers were requested to adhere to teaching material, and they were directed to report whether and in which way they deviated from the teaching material. Based on teachers’ reports, we concluded that teachers closely adhered to the



teaching material and their deviations were minimal. All students took part voluntarily in the study. The participants were tested in their regular classrooms at two measurement points (T1 and T2). The pretest and posttest consisted of a structural and procedural system thinking questionnaire, which was exactly the same for both grades.

## **2.1. Sample**

Twenty one fourth-grade science classes from 15 German primary schools and 15 eighth-grade biology classes from 8 German secondary schools participated in the study. Secondary schools were both Academic track and non-academic track schools. Fourth graders ( $n = 406$ ) were 9 to 11 years old (mean age: 9.83 years;  $SD = 0.35$ ). Eighth graders ( $n = 418$ ) were between 13 and 15 years of age (mean age: 14.01 years;  $SD = 0.57$ ). Gender was distributed evenly in the fourth and eighth grades: 47.9% of fourth graders and 49.8% of eighth graders were female.

## **2.2. Instruments**

### *Operationalization of dependent variables structural and procedural system thinking*

A system thinking test was applied to assess structural and procedural system thinking. The structural system thinking questionnaire contained eight items (see App. A), six multiple choice items and two open ended items. The scale of structural system thinking items focused on the basic structure of the “blue mussel ecosystem”. The questions to assess structural system thinking were constructed to capture the ability to identify relevant system elements, simple relationships between facts (e.g., “How do Blue Mussels protect themselves from heat at low tide?”) and to understand systems’ separation from other surrounding systems. (e.g., “Which of these terms are

irrelevant for a Blue Mussel's life? Strike them out! Sea Star, foot, sand, human, air, water, oxygen, shell"). The questions to assess procedural system thinking were constructed to capture the ability to understand possible processes and behaviours within the system (e.g.: "Oysters are much stronger than Blue Mussels. Imagine Oysters displacing the mussels in a few years. What are the consequences for eider ducks?"). The procedural system thinking questionnaire contained five items, three of them were closed and two were open. The scale of procedural system thinking items (see App. A) aimed at the development of certain processes within the system. Aiming on the assessment of both structural and procedural system thinking, we avoided to provide knowledge about each functional chain within the system. For that, it is important to note that the process interactions, assessed within the procedural system thinking scale, were not part of the intervention unit. Those lessons served as knowledge provider but explicitly not as provider of procedural system knowledge. Consequently, the procedural system thinking items were prompting for something which wasn't presented in the lessons before and therefore had to be developed.

Table 1 shows the internal consistencies as Cronbach's alphas. The coefficients are low, because the students had to deal with different item formats and with a wide and diverse content framework, for example the respiration background of a blue mussel organism and the intertidal impact on a Wadden Sea ecosystem.

**Table1:** Internal consistencies for SST and PST

	cronbach's $\alpha$	
	pretest	posttest
SST	.52	.50
PST	.44	.59

For this reason, low coefficients are probably due to item diversity rather than to reliability. However, by focusing on comparison between groups, the coefficients indicated sufficient consistencies (Lienert & Raatz, 1994).

### **2.3. Analyses**

The multiple choice items differed in their numbers of answers just as in their numbers of points. To obtain a consistent metric item design, the items were categorized afterwards to a categorical level evaluation score of 0, 1 and 2 points. The open items were evaluated in the same way (0 = the answer was incorrect, 1 = the answer was partly correct, or correct but the reasoning was lacking, 2 = the answer and corresponding reasoning was correct).

To determine the rater agreement, inter-rater reliabilities were computed for open questions in both scales structural system thinking and procedural system thinking. 15% of the items were scored by two raters. Raters' individual proposition scores were compared by calculating unadjusted intra-class correlations. Intra-class correlation coefficients (ICCs) were substantial for all conditions. (structural system thinking: ICC= 0.862; procedural system thinking: 0.882).

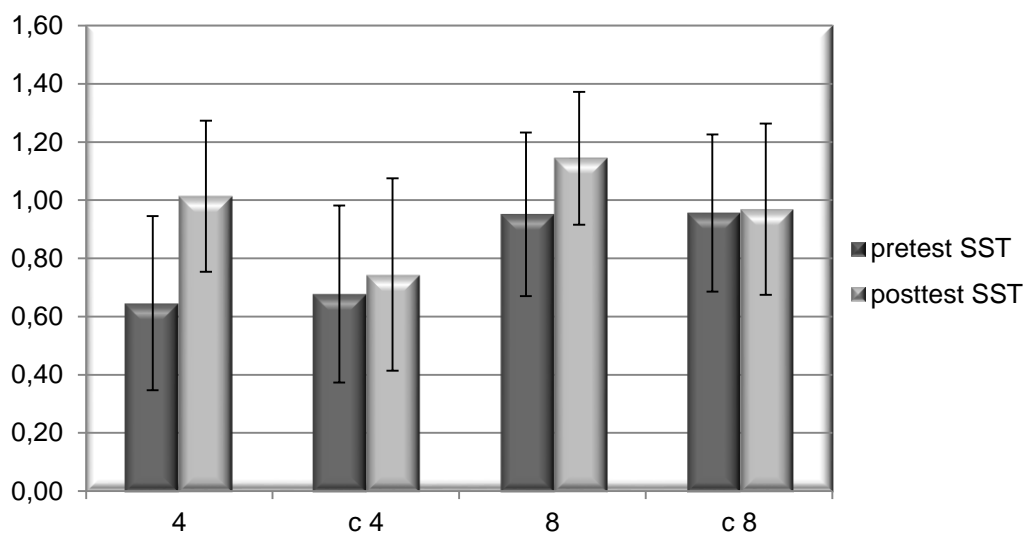
To analyze the covariance structure of our data, we used the MPlus program (Muthén & Muthén, 1998-2007). We used confirmatory factor analysis (CFA) in the context of structural equation modeling (SEM) to ascertain the degree to which the scoring structure fits to the hypothesized theoretical structure of system thinking. Regarding the first research question, we were testing for different model fits relating to different model structure of system thinking at one measurement point. A comparative fit index (CFI) above .95, a Tucker Lewis index above .95, and a root

mean square error of approximation (RMSEA) below 0.05 indicate a good fit (Hu & Bentler, 1999).

### 3. Results

#### 3.1. Dependent Variable: Structural System Thinking (SST)

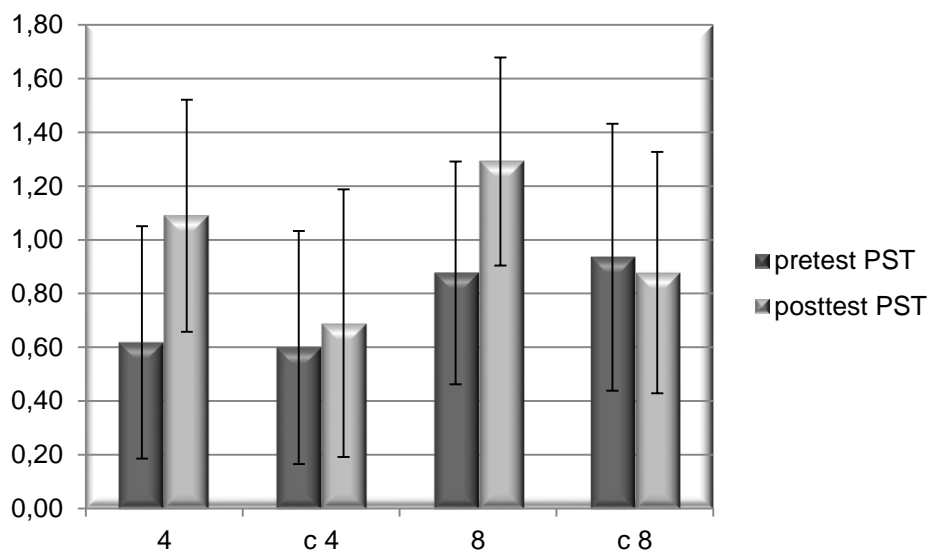
Aiming at the comparison of the structural system thinking performance level in grade 4 and grade 8, basically means and standard deviations for structural system thinking were calculated (Fig. 2). The level of structural system thinking at pretest is approximately the same regarding the experimental and control group at 4<sup>th</sup> and 8<sup>th</sup> grade. The gain in structural system thinking between pre- and posttest measurement is higher in grade four than in grade eight and significantly higher comparing both experimental groups to the control group. The cumulative level of structural system thinking both at pre- and posttest measurement is significantly higher in grade 8 than in grade four. (Fig. 2).



**Figure 2:** Means (standard deviations) concerning the dependent variables structural system thinking (SST) in grade 4 and grade 8

### 3.2. Dependent Variable: Procedural System Thinking (PST)

The same was done with the procedural system thinking performance level in both grades, means and standard deviations for procedural system thinking were calculated (Fig. 3). The level of procedural system thinking at pretest is approximately the same regarding the experimental and control group at 4<sup>th</sup> and 8<sup>th</sup> grade. The gain in procedural system thinking between pre- and posttest measurement is significantly higher in grade four than in grade eight and significantly higher comparing both experimental groups to the control group. The cumulative level of procedural system thinking both at pre- and posttest measurement is significantly higher in grade 8 than in grade four.

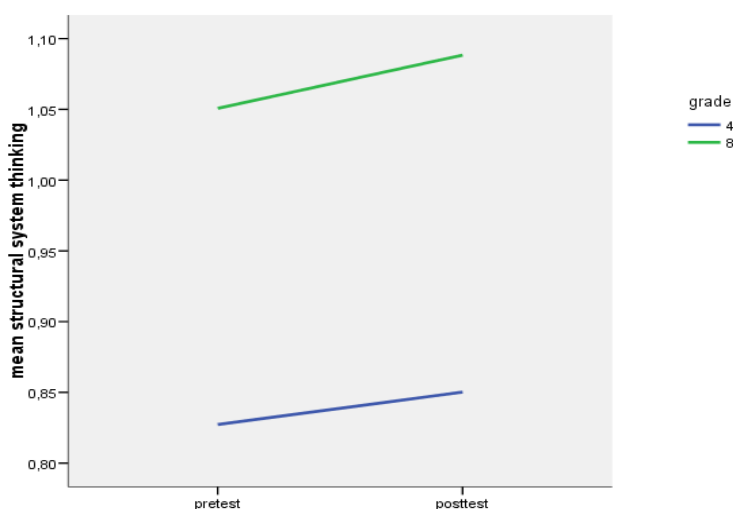


**Figure 3:** Means (standard deviations) concerning the dependent variable procedural system thinking (PST) in grade 4 and grade 8

### 3.3. Effects of grade on structural and procedural system thinking

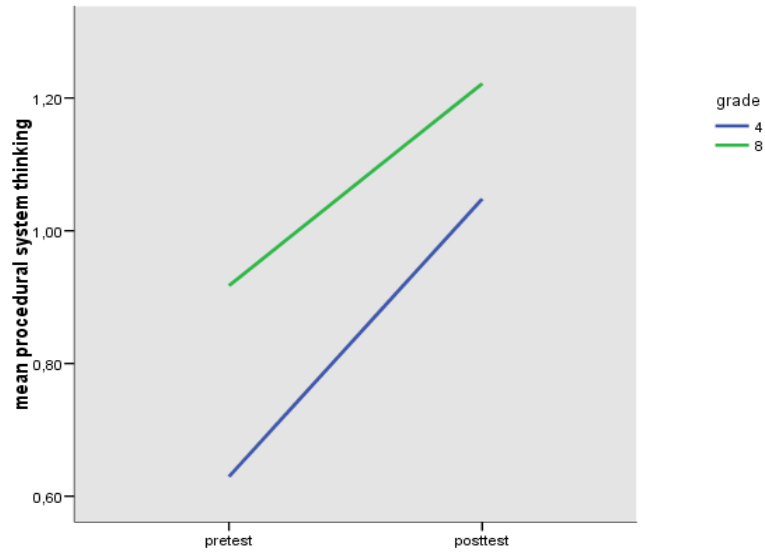
A repeated measures *MANOVA* with the factors *structural and procedural system thinking (pretest – posttest)*, the factor *grade (4<sup>th</sup> and 8<sup>th</sup> grade)* and Intelligence as covariate was used to analyze grade effects on structural and procedural system thinking.

There was a statistically significant high main effect of grade ( $F(1,455)=115.558$ );  $p < .01$ ;  $\eta^2 = .20$ ). Concerning the effect of grade on structural system thinking, there was no statistically significant SST by grade interaction, whereas results show a statistically significant PST by grade interaction (Pillai's trace, ( $F(1,455) = 17.389$ ;  $p < .01$ ;  $\eta^2 = .37$ ).



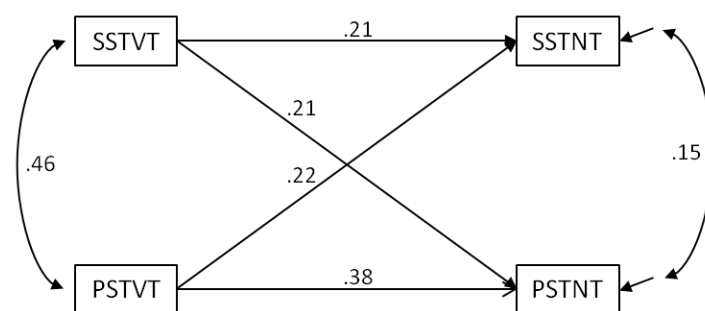
**Figure 4.:** Estimated means of structural system thinking at pre- and posttest measurement in 4<sup>th</sup> and 8<sup>th</sup> grade.

Interestingly, estimated means of PST (Figure 5) reveal that 4<sup>th</sup> graders increase of mean PST level from pretest to posttest measurement is significantly higher than 8<sup>th</sup> graders increase of mean PST level is. However, according to structural system thinking, the mean level of SST is higher in grade 8 than in grade 4 (Figure 4) and the gain of mean structural system thinking through intervention unit is approximately equal.



**Figure 5.** : Estimated means of procedural system thinking at pre- and posttest measurement in 4<sup>th</sup> and 8<sup>th</sup> grade.

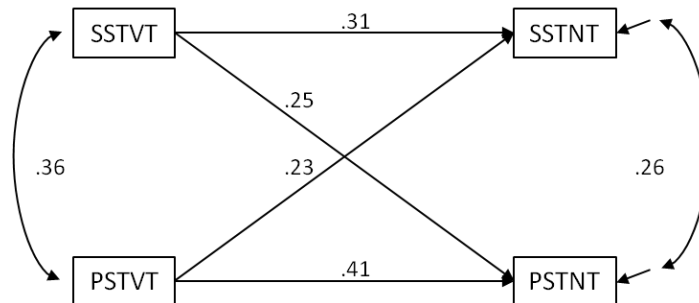
In order to test for the internal structure of system thinking, a structural equation model was specified. Correlation coefficients display a bidirectional relationship between structural and procedural system thinking in 4<sup>th</sup> grade (Fig. 6). Moreover, the strength of correlation between both factors is decreasing from pre- to posttest measurement.



**Figure 6:** Relations between structural and procedural system thinking in 4<sup>th</sup> grade

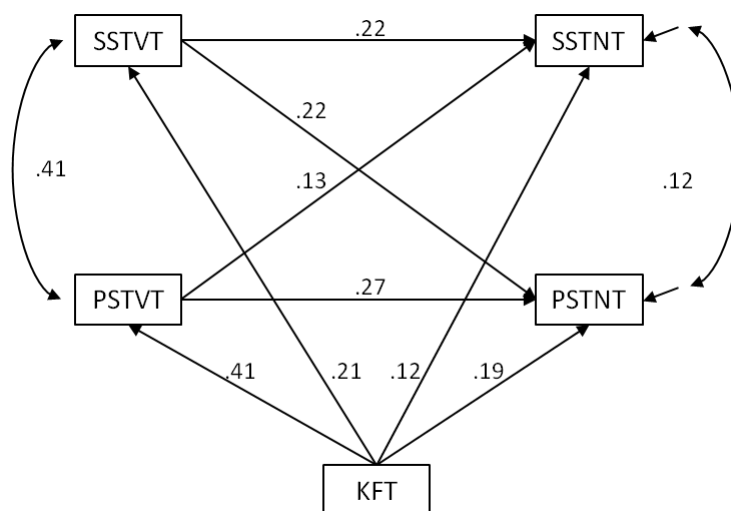
Similar results can be observed for 8<sup>th</sup> grade's analysis. The correlation between both factors at pretest measurement is less compared to 4<sup>th</sup> grade but the decrease from pre- to posttest measurement is a little bit lower than in 4<sup>th</sup> grade, resulting in a higher

correlation at posttest measurement. Nevertheless, a bidirectional relationship can be observed here, too (Fig. 7).



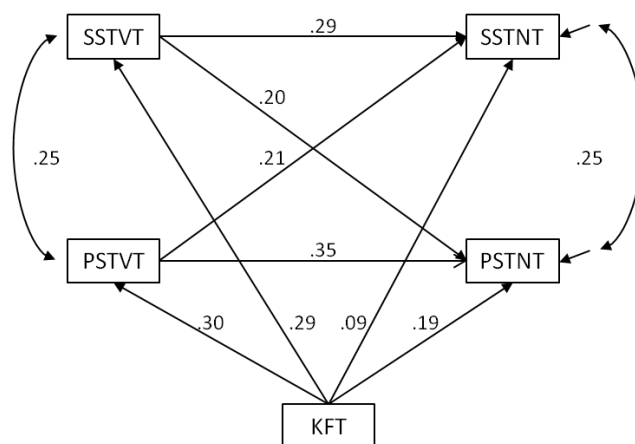
**Figure 7:** Relations between structural and procedural system thinking in 8<sup>th</sup> grade

Regarding to the influence of general cognitive abilities on the internal structure of system thinking, additionally the factor “KFT” was included into the structural equation model of system thinking for 4<sup>th</sup> grade (Fig.6) and 8<sup>th</sup> grade (Fig.7).



**Figure 8:** Relations between structural and procedural system thinking in 4<sup>th</sup> grade





**Figure 9:** Relations between structural and procedural system thinking in 8<sup>th</sup> grade

Including the factor of cognitive abilities displays a medium correlation between “KFT” and both factors of system thinking at both measurement points. But essentially, it doesn’t affect the structure pattern both in grade four and in grade eight (Fig. 8 and Fig. 9).

## 4. Discussion

### 4.1. Influence of grade on dependent variables of structural and procedural system thinking

A primary aim of the study was to test for differences between 4<sup>th</sup> and 8<sup>th</sup> grade students concerning the general level of system thinking. Therefore, the dynamic and complex system of blue mussels in the Wadden Sea ecosystem was implemented as intervention unit in the biology curriculum of 4<sup>th</sup> and 8<sup>th</sup> graders. The unit involved classroom experiments, direct interactions with living animals and system component and integration of fundamental knowledge about blue mussel and Wadden Sea ecosystem. The posttest results show that generally 8<sup>th</sup> graders are able to develop system thinking on a higher level than 4<sup>th</sup> graders. These differences

are rooted in different levels of stage of development that are closely related to different levels of general cognitive abilities. Nonetheless, results show interesting aspects according to the development of system thinking in different grades. First of all, though it was to be expectable that system thinking appears at a different level in both grades, posttest results both of structural and procedural system thinking of 4<sup>th</sup> graders are higher than those of 8<sup>th</sup> graders before intervention. Obviously, these skills of system thinking don't only improve by increasing age but need to be learned (Assaraf & Orion, 2010). Moreover, the improvement of both system thinking skills was different in both grades. Interestingly, the gain of structural system thinking was approximately equal in both grades. Contrary to that, 4<sup>th</sup> graders gain of procedural system thinking, although the starting point was similar to the starting point of structural system thinking, throughout the intervention unit was significantly higher than in grade 8. Therefore, 4<sup>th</sup> graders obviously benefit to a higher extent from the input during intervention unit. They succeeded more effectively in generating relationships and developmental processes from a structural fundament. These outcomes support findings that emphasize young children's' ability of abstract thinking (Cuevas, Lee, Hart, & Deaktor, 2005). Thus, this study provides valuable information concerning the question to which extent elementary students are able to convey system thinking perceptions. Regarding to 8<sup>th</sup> graders, findings reveal that they concentrate evenly on assimilating structural aspects and developmental processes of the system. These assumptions concur with those of Eberbach & Crowley (2008) who recognized similar distributions at junior high school levels. Nevertheless, different levels of gain in system thinking in different grades lead to the question of whether or not the internal and longitudinal structure pattern in those grades is identical. The relationship between structural and procedural system

thinking is still under debate. Many of these publications describe a close relationship between both factors of system thinking (e.g. Assaraf & Orion, 2005; Eilam, 2012; Evagorou et al., 2009) and therefore prognosticate a challenge of empirically proving a multifactorial structure. In this study, structural and procedural system thinking were modeled in a cross-lagged-panel design. This allowed us to better account for predictive relations from structural to procedural system thinking and vice versa. The results of this study strongly support an iterative model in both grades, with bidirectional relations between structural and procedural system thinking. Particularly with respect to general cognitive abilities the aspect of model structure is interesting. This factor didn't influence the bidirectional pattern of system thinking in both grades, which indicates a construct stability that is supported by but not existing of general cognitive abilities. Moreover, the predictive relations were not only bidirectional but almost symmetrical. These findings support the importance of evaluating structural and procedural knowledge together. Otherwise, the assessment of only one aspect of system thinking may turn out to a fragmentary picture of system thinking development.

The iterative model helps to understand the procedure of knowledge development (Rittle-Johnson & Siegler, 1998), as so the development of system thinking. At first the initial system thinking tends to be constricted, leaving it unclear which type of knowledge is responsible for a given pattern of answers. It then depends on the previous knowledge in a domain, whether structural or procedural system thinking will be the one to emerge first. These findings raise the following questions: Which processes underlie the influence of initial structural system thinking improving procedural system thinking and vice versa? One possible explanation is that students' structural knowledge regulates the tie of familiar procedures with the

challenge of new procedural knowledge. In this way, students might transfer known relevance of system relations to new problems (Anderson, 1993) or system procedures and thereby benefit from structural system thinking in a procedural way. Another operation behind the improvement of procedural system thinking through structural system thinking may be elaborated choices among different system procedures. It is known from the field of mathematics that conceptual knowledge students' choice among substitute procedures (e.g. Lemaire & Siegler, 1995). Thus, improved structural understanding of a system reduces the probability of generating incorrect procedures and supports focusing on correct system procedures or cycles. Considering the second cross section of the bidirectional model includes mechanisms of linking procedural system thinking with improvements in structural system thinking. A possible mechanism in this way is the perception of food web processes with the Wadden Sea system. Thus, students' understanding of web configuration in temporal processes may in turn enhance their understanding of causality and structural relationships and strengthen the anticipation of distinct elements. For example, the understanding of the cycle relation between blue mussels, oysters and eider duck mortality may strengthen the idea about oysters and blue mussels' non aggressive relationship and the impact of reduction on eider ducks if they rely on only one main resource. This anticipation of procedural system thinking in turn unravels the indirect complexity of web system processes and helps to understand individual implicit interactions (Reiner & Eilam, 2001). These aspects tie in with other authors that document positive influences of a high domain expertise, facilitating the assimilation of new knowledge in an interrelated knowledge structure (Linn, 2006; Schneider & Stern 2009). Another possible explanation for the strengthening of structural system thinking through procedural system thinking is that

improvement in understanding system processes may enlighten students' misunderstanding (e.g. Resnick et al, 1989) that lead to prior incorrect procedures (Rittle-Johnson, Siegler & Alibali, 2001). If students understand a systemic process or developmental procedure and its result, it helps to transfer such principles across structural relationships that were misunderstood before. In doing so, gains in structural system thinking arise through procedural understanding. At this point the explanatory power of the study would have been amplified through explanatory sequences of students, in which they were urged to explain the concepts and procedure they use. This way of reflection on the individual base of facts, concepts and procedures has been proven to lead to learning improvement (Pine & Messer, 2000; Renkl, 1997). Consequently, further research should notion the potential of effectively explaining the answers during intervention (Siegler, 1995).

To sum up, there are multiple conceivable operations leading to a bidirectional relationship between structural and procedural system thinking. The impact of structural system thinking on procedural system thinking may be defined through increasing options of correct relations, thereby strengthen the adaption of familiar procedures with the challenge of new procedures. In turn, gains in procedural system thinking may be influenced through representation of system procedures that facilitates the reflection on how these procedures function. Consequently, this understanding supports the capturing of prior misconceptions and improved structural system thinking.

However, each factor of system thinking facilitates the development of the other one, a relationship that is clearly reflected by positive and high correlations at both measurement points. The design of this study cannot provide appropriate data to check for the viability of each of these underlying mechanisms. This point might

meet an interesting field of future research that might specifically qualify the partial nature of system thinking, particularly the influence of each type of previous knowledge on the acquisition of both types of system thinking. Another interesting perception gained from this study's' data. There is a causal relation between the factor of general cognitive abilities and both structural and procedural system thinking. But the effect of general cognitive abilities is surprisingly low (max. .41 in 4<sup>th</sup> and max. .30 in 8<sup>th</sup> grade) and doesn't influence the relationship pattern between structural and procedural system thinking. Consequently, only a part of structural and procedural system thinking's variance can be explained by general cognitive abilities, a fact that is mirrored by similar values in 4<sup>th</sup> and 8<sup>th</sup> grade.

#### **4.2. Conclusion, limitations and implications for system thinking education**

The understanding of a complex system structure is engraved by all elements of a system and of the system as an ensemble. The current findings allow us to follow this improvement of understanding as simultaneously bidirectional – from elements to processes and vice versa. Consequently, a meaningful assimilation of system thinking in the field of biology requires a bidirectional way of instruction. The incorporation of general elements and concepts should be accompanied by the integration of higher order structures and concepts (Eilam, 2012). This would implicate a simultaneous bottom up - top down strategy that might facilitate students' improvement in both aspects of system thinking more effectively, because it enables them to directly benefit from each knowledge achievement. Moreover, the additional implication of systemic metaknowledge might support the transfer of general system concepts and procedures to a specific content. Multifaceted instructional modes might be helpful to design general system characteristics. Concept maps for

example represent a useful tool to illustrate a web structure, including feedback mechanisms as well as macro- and microscopic level expression (Brandstädter, Großschedl & Harms, 2012). Additionally, the use of a live-model as this study is based upon, allows a lot of opportunities like experiencing to know real organisms, their visual nature and behavior. On the other hand, the expressiveness concerning whole systems' components and processes is restricted and not manageable as classroom experience. Therefore, the application of computer simulation is a possible tool to add to an extensive system impression (Azevedo, Winters & Moos, 2004; Riess & Mischo, 2010; Stieff & Wilensky, 2003) that has been proven to stimulate students' performance. Since this study lacks the implementation of different interventional combinations, further research is needed to investigate the use of such combinations on both aspects of students' system thinking. In addition, further research might investigate to which extent students could benefit from their system thinking improvement in one class up to subsequent classes to evaluate the development of system thinking different developmental stages precisely. This might enlighten the wide field of transfer in the context of system thinking and may contribute to the ongoing question how students learn, reflect and combine knowledge in different disciplines in the area of science. Investigations like this in turn might serve supportive instructional solutions concerning the learning of systems' core principles. The results of this study provide valuable information about how structural and procedural system thinking shape the whole construct of system thinking. This is both of theoretical and practical relevance since the understanding of how students improve their system thinking contributes to a better understanding of how to effectively scaffold students in their general learning progression.

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## DISCUSSION AND PROSPECTIVE IMPLICATIONS

This dissertation addresses the characterization of system thinking in the context of biology education at elementary and secondary school level. The overall aim was to provide an empirical foundation for the model structure of system thinking leading to a deeper insight in the internal construct relationships. The following chapter will present the results of the related studies, including the discussion of methodological constraints as well as further research implications. A general conclusion will outline the empirical results on deductions concerning both an effective dealing with complex systems in educational contexts and a basis for prospective scientific research.

### **1. Discussion of the present studies**

The central focus of the present dissertation was to develop an appropriate assessment framework based on an ecosystem context to characterize the model structure of system thinking, particularly comparing elementary and secondary school students. All investigations were based on a system oriented intervention unit “The Blue Mussel in the context of the Wadden Sea ecosystem”, offering different perspectives on a multilevel system hierarchy with dynamically interacting elements. Based on the mediation of the essential content knowledge, the introducing of across-level-interactions of elements and processes provided an appropriate basis to introduce system thinking, thereby facilitating a holistic understanding of complex ecosystems and predictive ecology (Chapter 1). The starting point for an analysis of system thinking was set by investigating suitable assessment practices. Apart from developing a questionnaire, containing multiple choice as well as open question, three different Concept Mapping practices (paper-pencil highly directed, computer

based highly directed, paper-pencil non-directed) were evaluated concerning a) their influence on students' performance in Concept Mapping and b) their influence on the validity of students' Concept Mapping regarding procedural and structural system thinking (Study 1). Subsequently, the hypothesized model structure of system thinking was examined and reviewed with regard to measurement invariance both across two measurement points and across elementary and secondary school students (Study 2). Moreover, structural analysis of system thinking served as point of reference for further investigations concerning the internal relationships between structural and procedural system thinking (Study 3). Referring to the comparison of elementary and secondary school students (Study 1, 2 and 3) and regarding to their general level of system thinking, developmental dependencies between structural and procedural system thinking were investigated, in addition with particular focus on the influence of general cognitive abilities.

Detailed results and discussion will be presented in the next section:

### **1.1. Study 1**

Study 1 investigated appropriate system thinking assessment methods. A questionnaire was evaluated as well as three different Concept Mapping practices. Regarding to the first research question, study 1 focused on the comparison of the medium (computer vs. paper-pencil) and/or the directedness (highly directed vs. nondirected) with respect to students' Concept Mapping performance. Results concerning the mediums' influence revealed that students using a computer based Concept Mapping practice performed slightly better than those using a paper based practice. The results were confirmed both by elementary and secondary school

students. With respect to the influence of directedness, results revealed no influence of directedness on Concept Mapping performance in both school levels.

The second research question focused on the validity of those three Concept Mapping practices (in form of a Proposition Accuracy Score) concerning system thinking assessment. Here, paper-pencil based practices led to a higher validity for procedural system thinking at secondary school level, whereas there were no differences concerning the medium in elementary school level. With regard to the validity on structural system thinking, results of paper-pencil based practices slightly outperformed computer-based practices in both school levels. Finally, concerning the influence of directedness on the validity of system thinking assessment, highly directed Concept Mapping practices in both school levels outperformed nondirected practices, for structural system thinking as well as for procedural system thinking.

Additionally, results of study 1 adduced evidence for a two-factorial model structure of system thinking that served as point of reference for the subsequent studies 2 and 3.

## **1.2. Study 2**

Based on study 1 and its first indications for system thinking's model structure, study 2 aimed to collect evidence about the (1) the structure and (2) the construct validity of system thinking using factorial invariance across two measurement points and (3) across two different school levels. Therefore, the research questions were: (1) whether a two-dimensional model structure fits the data better than a one-factor model, including the comparison between elementary and secondary school level and (2) whether there is evidence for measurement invariance regarding the two-factorial model of system thinking and (3) if the two-factorial model of system thinking



is invariant across different grades. A structural equation modeling approach generated results confirming the assumptions made in study 1 concerning a two-factorial model structure of system thinking (research question 1). The validity of the two-factorial model structure of system thinking was proven by measurement invariance across two-measurement points (research question 2) as well as across both school levels, i.e. for elementary as well as for secondary school students (research question 3). This construct stability provided fundamental information about the development of system thinking. Remaining stable throughout two measurement points, the two-factorial pattern didn't melt into one factor in the posttest measurement, even after an immense knowledge input was provided in the intervention phase. This leads to the assumption that newly acquired knowledge, although being indeed an indispensable part of system thinking, seemed to be added to without superposing the two-factorial pattern system thinking as one "big" factor. Hence, the question aroused how structural and procedural system thinking relate, determine, and influence each other. Beyond that, the question raised whether and to which extent there is an influence of general cognitive abilities. To summarize, study 2 offered an essential and empirically proven basis concerning the internal model structure of system thinking that was referred to in study 3.

### **1.3. Study 3**

Study 3 directly followed from findings of study 2, investigating the internal relationship of structural and procedural system thinking. A close connection between structural and procedural system thinking in form of a high correlation supported the theoretical assumption of a bidirectional model structure, referred to as iterative model. Additionally, a comparison between elementary and secondary school

students was of interest here, leading to the investigation of a possible influence on general cognitive abilities. Therefore, three questions had to be answered to characterize the internal model structure of system thinking. (1) Which general level of structural and procedural system thinking do elementary students achieve in comparison to secondary students? (2) Is there evidence for a bidirectional relationship between structural and procedural system thinking both in 4<sup>th</sup> and 8<sup>th</sup> grade? (3) How do general cognitive abilities contribute to the internal structure pattern of system thinking both in 4<sup>th</sup> and 8<sup>th</sup> school level? Results showed that both grades differently improved their system thinking skills. Although the gain of structural system thinking was approximately equal in both grades, 4<sup>th</sup> graders gain of system thinking was significantly higher than those of the 8<sup>th</sup> graders. These results lead to the assumption that 4<sup>th</sup> graders succeeded more effectively in generating relationships and developmental processes from a structural fundament. Thus, this study provided valuable information concerning the question to which extent elementary students are able to convey system thinking perceptions. Regarding to 8<sup>th</sup> graders, findings revealed that they concentrated evenly on structural and procedural system thinking. Additionally, results confirmed the hypothesized bidirectional structural pattern of system thinking in both grades/school levels, which was supported but not modified by general cognitive abilities.

Hence, the results of study 3 were pointing to the importance of evaluating both structural and procedural knowledge to avoid a fragmentary picture of system thinking development. Indeed, these results allowed for interpreting the structural pattern but they did not give an answer to the question whether structural or procedural system thinking will be the one to emerge first, or, if they emerge simultaneously. Thus, results of study 3 clearly pointed to further investigations on

identifying processes that underlie the emergence of initial structural system thinking and improve procedural system thinking and vice versa. The following chapter is going to address this research demand concerning system thinking's precise development. Additionally, taking previous methodological constraints into account, a general conclusion will combine the potential of those present results with implications for future system thinking research areas.

## **2. Challenges for future investigations on system thinking**

The results of this present dissertation provide an important contribution concerning the characterization and the development of system thinking. By analyzing design-based and methodological constraints, indications for future research offer worthwhile links to diverse scientific dimensions and may promote the transfer of complex system principles to enhance educational settings.

### **2.1. Strengths and weaknesses of the present studies indicating issues for future research**

The studies presented here are based on a classroom setting, using an ecosystem intervention unit to provide comparable knowledge acquisition. To be able to integrate the intervention unit into the current curriculum, it comprised a maximum of eight lessons, excluding the assessment time. This is an important aspect for further research regarding the decision which study type to conduct. One has to decide between extended large scale classroom studies and small-scale studies that could be conducted as laboratory experiments. Also a combination of classroom and laboratory experiments might be reciprocally useful allowing for gradual knowledge construction and reconstruction mediated through intent discourses (Eilam, 2012) on

the one hand and to attain a sustainable understanding of system thinking's development and affecting factors on the other hand (Brown, 1992). Moreover, the intervention unit presented here was constructed to fundamentally provide the essential ecosystem knowledge without making general system principles explicit in order to avoid training effects. But, since structural transparency is a fundamental feature regarding to system based learning environments (Größler, Maier, & Milling, 2000), the implementation of this system-oriented meta-level should be taken into account for prospective investigations. To avoid training effects in such implementations, it might be useful to broaden the content of the assessment instruments to a completely different context. In doing so, results will additionally offer insights into the transfer of complex system principles into new contexts. To gain a higher level of transfer into educational settings, the influence of teachers' professional content knowledge should be taken into account as well (Hmelo-Silver & Azevedo, 2006; Park & Oliver, 2008). A multilevel approach might be a useful way to investigate those relationships.

A central part of the intervention unit was the integration of living animals (*Mytilus edulis* – blue mussel) to enable direct contact with those organisms of the teaching material (Klingenberg, 2008). Such primary experiences are known to have a close connection to students' everyday life (e.g. Storrer & Hirschfeld, 2007) and are effective promoters for students' intrinsic motivation (Wilde, Hussmann, Lorenzen, Meyer, & Randler, 2012). The blue mussel was chosen to provide a biological content that is not an obligatory part of the curriculum and therefore was of low risk to confound the results regarding students' previous knowledge. Additionally, these animals are relevant in the local situation of Schleswig Holstein that is framed by the Wadden Sea at the western coast side of Germany. Thus, the use of real system

experience, while being a successful factor in educational settings, is a recommendable supplement for further system thinking investigations, whereupon getting in contact with a real ecosystem (Assaraf & Orion, 2005) is a suitable alternative for keeping organisms within the classroom.

The most challenging factor regarding the development of system thinking was the understanding of nonlinear and feedback loop processes within the system, a preservative effect in current research findings (e.g. Assaraf, & Orion, 2010; Evagorou, Kostas Korfiatis, Nicolaou, & Constantinou, 2009; Hmelo-Silver, & Pfeffer, 2004). To meet these challenges more effectively, especially in time constraining conditions, the application of a computer based system simulation program might facilitate the understanding of complex phenomena's behavior (Booth Sweeney & Sterman, 2007; Goldstone & Wilensky, 2008; Riess & Mischo, 2010). To generate critical aspects of natural systems' behavior, so called *agent-based modeling* (ABM) (Epstein, 2007; Miller & Page, 2007; Railsback, Lytinen, & Jackson, 2006) programs have been proven as supportive tools. Using these model systems, the macroscopic system behavior can be generated through the behavior and interactions of lower-level elements. In doing so developmental processes such as predator and prey relationships can be plotted and give an impression about how the system will behave in the future, based on the current status (Wilensky & Reisman, 2006). Concerning prospective research on system thinking development, the ABM technology allows for transfer of grounding system principles across other scientific areas including natural sciences as well as social sciences and engineering (Epstein & Axtell, 1996; Ottino, 2004). Moreover, such system modeling strategies may be conceivable particularly in contexts of age dependent development of system thinking, because they support "low threshold" (novice) as well as "high ceiling"

(expert) system exploring and generating (Tisue & Wilensky, 2004). Thus, ABM strategies, while operating at a high variety of levels to analyze and explore complex system situations, offer a suitable system oriented approach for educational settings (Abrahamson & Wilensky, 2004). Additionally, further research is needed here to support teachers effectively in applying and integrating computer simulation programs into educational settings (Mandinach & Cline, 2000).

Due to the design of the studies presented here, only two measurement points were taken into account for the assessment of system thinking. Thus, another point for methodological amplification in future system thinking research settings is to formatively assess the development of system thinking at several measurement points throughout the intervention, which possibly could be integrated into the computer program. In doing so, the indicative power of future studies might be extended through explanatory sequences of students, in which they were urged to explain the concepts and procedure they use. This way of reflection on the individual base of facts, concepts and procedures has been proven to lead to learning improvement (Pine & Messer, 2000; Renkl, 1997). Consequently, further research should make use of the potential of effectively explaining the answers during intervention.

Since having students to inform, interpret and correct system situations is regarded as supportive strategy to enhance students' system understanding, such computer based methods effectively point to this advantage (Jacobson & Wilensky, 2008). This could be accompanied by extra space for discussion and communication to enhance the integration of system based interpretations.

In conjunction with prospective projects focusing on system thinking assessment the implication of additional assessment instruments as for example the

observation through ABM strategies as mentioned above would strengthen the validity as well the explanatory power of test results relating to system thinking development. Apart from study 1, the findings shown here were based on a questionnaire that was restricted to only 13 items (8 items for structural system thinking and 5 items for procedural system thinking). Aiming at the multifaceted background of an ecosystem unit, these items were designed to compass this systems' heterogeneity, but this consequently led a low item homogeneity, which in turn was mirrored by a low reliability. This is an important aspect for future research to cope with and may be intercepted by adding both more items to strengthen the questionnaire and adding additional test instruments. Moreover, this would contribute to the convergent validity of system thinking, another important aspect with respect to the heterogeneous field of system thinking research with using a remarkable variety of assessment instruments. To increase not only the convergent but also the discriminate validity of system thinking, the following indications should contribute to a methodological framework for further research projects.

## **2.2. Cognitive challenges in system thinking development affecting other areas of research**

Regarding the constraints mentioned above, diverse aspects to deal with in further system thinking research projects arise, offering different issues for future research, implicitly or explicitly referring to other areas of research. Concerning an effective learning of complex systems in context of the above mentioned simulation programs, several developmental subjects are required: general knowledge about the nature of models, content knowledge, general skills (cognitive and metacognitive skills and motivational strategies) and scientific reasoning skills (hypothesis

generation, data collection, analysis and result communication) (Azevedo, Cromley, Winters, Moos, & Greene, 2005). These skills contribute to the cognitive challenge of understanding complex systems, which means to reduce complex phenomena to a structural and developmental pattern that is not the true structure of the phenomenon. This is the key subject of modeling abilities that students have to develop in order to understand complex systems. Consequently, from a modeling point of view, understanding complex systems' emergent properties means to understand these properties as emerging from the whole instead of emerging from single elements' properties (The whole is more than the sum of its parts.) (Lesh, 2006). Thus, mental models are an important representation of structure, development, and changes concerning the individual assumptions about complex systems: "A mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external dynamic system (historical, existing or projected). The internal representation is analogous to the external system and contains, on a conceptual level, reinforcing and balancing feedback loops that consist of causally linked stocks, flows, and intermediary variable. The causal links are either positive or negative, are either linear or non-linear, and can be delayed" (Doyle & Ford, 1999, p. 414). Thus, system thinking and complex systems emergent properties are closely linked with other kinds of cognitive constructs, concepts, and abilities. Therefore, system thinking research should extend to these latter abilities. One possible way to examine students' understanding of complex systems' principles is first: to understand their mental models (Groesser & Schaffernicht, 2012) and second: to understand and overcome associated problems with systems' modeling. One way to investigate students' failures in understanding and modeling systems in future research might be a problem solving approach. This



approach might support students in clarifying their system understanding by applying models of the system to certain system problems (Jonassen, 2003; Paton, 1996). A problem solving approach usually elicits students' conceptions, leading to realize inconsistencies in their conceptual structure. In doing so, solving system problems challenges students to create their own hypotheses and to precisely visualize the problem through iteratively testing and revising cycles (Lesh & Harel, 2003). This in turn allows for conceptual change through representing systemic understanding dynamically (Vosniadou, Skopeliti, & Ikospentaki, 2004). Therefore, future research should investigate system thinking development with respect to the development of problem solving strategies and abilities. An interesting way of further research would lead to treat problem solving abilities as an independent variable, testing its influencing potential on system thinking as a dependent variable. Moreover, modeling abilities should be included to examine mediating or moderating effects concerning this relation. To gain applicable information, a separation of labor could be a promising strategy. Large scale assessments for example could focus on valid measures of system thinking in relation to other psychological constructs like problem solving abilities, by controlling for modeling abilities. Simultaneously conducted laboratory experiments could contribute to in depth investigations of the underlying cognitive processes, whose development cannot precisely be examined by means of one-lesson- tests. This might be a promising multimethod approach to enhance the ecological validity and to handle diverse requirements with regard to differences in age and developmental stages (English & Watters, 2004). Moreover, this would be a research strategy contributing to the question of whether system thinking development can be considered as occurring 'bottom up' or 'top down', which consequently leads to examining the role of analysis and synthesis (Verhoeff, 2003)

in system thinking development. Additionally, the understanding of how students develop system thinking as well as the understanding of how system thinking supports the learning of complex systems offers effective approaches to advance alternatives to traditional curricula and educational settings. Based on this theoretical and empirical fundament, it might be possible to facilitate students' learning about complex systems and additionally benefit from complex system principle to enrich the general understanding of how students learn.

### **2.3. Implications for teaching practice**

The essential findings from this thesis were seized to derive implications for system oriented teaching practice to support system thinking development at school. Nowadays, biological research is becoming a more integrated structure concerning the levels of biological organization. Moreover, the approach of the biological research today is interdisciplinary and system oriented, focusing on processes and interactions of biological systems on various scales, from the molecular scale to global environmental systems. Therefore, contemporary curricula should offer opportunities to learn how to deal with such complex system's structure and development.

Based on a structural equation modeling analysis in this thesis, an invariant two-factorial model structure of system thinking has been proven by measurement invariance both at elementary as well as at secondary school level. This is a valuable information concerning the system oriented teaching and learning process at school, because it implicates to avoid the mediation of isolated facts and concepts and to focus on a coherent understanding of biological systems and processes. Many biological books are asking too much of students' learning abilities by offering too

much facts and detailed concepts, separated in different topics, thereby leading to an overload of acquisition (Verhoeff, 2003). From a system oriented point of view, this thesis shows that one should start to establish system thinking as definite part of the biological curriculum as early as in elementary school level. Results of this thesis revealed that it's possible to gain a deeper system understanding and to develop both structural and procedural system thinking even at this developmental stage. Moreover, this thesis offers a possibility how to introduce a holistic understanding of biological phenomena both at elementary and secondary school level.

The construct stability of system thinking shown in this thesis provides fundamental information about the development of system thinking. The two-factorial pattern has been proven as stable throughout two measurement points and didn't melt into one factor, even after an immense input of content knowledge. But there was also evidence for a close relationship between both parts of system thinking, leading into a high correlation and a bidirectional structure pattern. Consequently, an important claim is the simultaneous introduction of structural and procedural system relations to support coherent system thinking in form of cross-level-thinking. Therefore, introducing and supporting system thinking at school has effects on the biology curriculum approach concerning the content and the arrangement.

Biological issues are open and dynamic systems, therefore they could be acquired from a systems' perspective, which means to cover the hierarchical structure from both an analytic and synthetic point of view. For example, ecology, evolution, cell biology and behavior are a few issues being suitable to be reconsidered from a systems' perspective. Crossing different levels of the biological issue to include organismic understanding might facilitate the development of system thinking. Additionally, the use of a computer based system simulation program might

facilitate the understanding of biological phenomena's behavior (Booth Sweeney & Sterman, 2007). Using such a program, the macroscopic system behavior can be generated through the behavior and interactions of lower-level elements, clarifying the ascending and descending between different levels. In doing so, developmental processes such as predator and prey relationships can be plotted and give an impression about how the system will behave in the future, based on the current status (Wilensky & Reisman, 2006). Moreover, a Computer based system modeling strategy is recommendable concerning the age dependent development of system thinking, because it supports "low threshold" (novice) as well as "high ceiling" (expert) system exploring and generating (Tisue & Wilensky, 2004).

Regarding the conceptualization of biology education including a system perspective, especially the development of feedback-loop-thinking across different system levels is of central importance. Consequently, abstract system modeling may be a useful way to gain a holistic understanding of biological phenomena. Therefore, facilitating system thinking development requires introducing students in thinking forward and backward while using intermediate and abstract models, for example in form of computer based system models.

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## List of Publications

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## **Erklärung**

Hiermit erkläre ich, dass ich die vorliegende Dissertation nach den Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft selbst verfasst habe. Dabei habe ich keine Hilfe, außer der wissenschaftlichen Beratung durch meine Doktormutter Prof. Dr. Ute Harms in Anspruch genommen. Des Weiteren erkläre ich, dass ich noch keinen Promotionsversuch unternommen habe.

Teile dieser Arbeit wurden bereits veröffentlicht oder zur Publikation eingereicht.

Kiel, den

Kristina Fraune