The influence of representation control on task performance and learning

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Summary

Although infographics are often used in digital newspapers or magazines to communicate information, users frequently have difficulties identifying the relevant information. Moreover, the spatial organization of the information in the infographic and the users´ requirements rarely match. One way to overcome these challenges might be to offer the users interactive control over the format and content of the representations. Representation control can be used to modify the infographics in order to externalize transformations that would usually have to be performed cognitively. This can enhance task performance, but it is unknown whether it facilitates or hinders learning of the underlying structure of the task. The objective of this dissertation was to examine the usage of representation control options and its effects on task performance and learning. In order to do so, I conducted three experimental studies with 650 participants in total. All studies revealed that users took the option to reorganize and reduce information in infographics in a strategic way. However, the availability of representation control improved only the performance in the task with a specific goal but not in the goal-free task. To test whether representation control also influences learning, I adapted a two-phase design with a practice and a testing phase in the third study. This experimental series revealed that practicing with representation control in general did not benefit learning. Participants who did not have representation control during testing could not benefit from their prior experience with representation control neither when solving the same task nor when doing a near transfer task. Comparing different forms of representation control revealed that the more automated types led to the best performance during the practice phase, but not during the testing phase. The results of my dissertation suggest that it is important to consider the type of task to be performed and to differentiate between task performance and learning when investigating

representation control or deciding whether representation control should be offered to the user.

Zusammenfassung

Infografiken werden häufig in digitalen Zeitungen oder Zeitschriften verwendet, um Informationen zu kommunizieren. Allerdings haben die Benutzer oft Schwierigkeiten, die relevanten Informationen zu identifizieren. Zudem stimmt die räumliche Anordnung der Informationen in der Infografik selten mit den Anforderungen der Nutzer überein. Eine Möglichkeit diese Schwierigkeiten zu verringern, könnte sein, den Nutzern interaktive Kontrolle über Format und Inhalt der Repräsentation zu bieten. Die Repräsentationskontrolle (eng. representation control) kann dazu genutzt werden, die Infografiken so anzupassen, dass Transformationen, die ansonsten kognitiv durchgeführt werden müssten, externalisiert werden. Dies kann die Aufgabenlösung erleichtern, jedoch ist unbekannt, ob es das Erlernen der zugrunde liegenden Struktur der Aufgabe erleichtert oder behindert. Das Ziel dieser Dissertation war es, zu untersuchen, ob Nutzer von Möglichkeiten zur Repräsentationskontrolle Gebrauch machen und welche Auswirkungen dies auf die Aufgabenlösung und das Lernen hat. Ich habe drei Experimentalstudien mit insgesamt 650 Teilnehmern durchgeführt. Alle Studien zeigten, dass die Nutzer von der Möglichkeit Gebrauch machten, die Informationen in Infografiken strategisch umzuorganisieren und zu reduzieren. Die Verfügbarkeit von Repräsentationskontrolle verbesserte jedoch nur die Leistung in der Aufgabe mit einem bestimmten Ziel, nicht aber in einer zielfreien Aufgabe. Um zu testen, ob Repräsentationskontrolle auch das Lernen beeinflusst, habe ich in der dritten Studie ein zweiphasiges Design mit einer Übungs- und einer Testphase umgesetzt. Diese Experimentalserie ergab, dass das Üben mit Repräsentationskontrolle im Allgemeinen nicht zum Lernen beitrug. Teilnehmer, die während der Testphase keine Repräsentationskontrolle nutzen konnten, haben von ihrer Erfahrung mit Repräsentationskontrolle weder bei der Lösung der gleichen Aufgabe noch bei einer nahen Transferaufgabe profitiert. Der Vergleich verschiedener Formen der Repräsentationskontrolle ergab, dass die stärker automatisierten Formen in der Übungsphase, aber nicht in der Testphase, zu den besten Ergebnissen führten. Die Ergebnisse meiner Dissertation verdeutlichen die Relevanz, die Art der auszuführenden Aufgabe zu berücksichtigen und zwischen Aufgabenleistung und Lernen zu unterscheiden, wenn Repräsentationskontrolle untersucht wird oder wenn entschieden werden soll, ob Repräsentationskontrolle dem Benutzer zur Verfügung gestellt wird.

Introduction

In our everyday life, we are confronted with plenty of visual representations. For instance, in the morning, before suiting up, we check the weather forecast for the day. We get a collection of visual representations: a map with symbols representing the actual and future conditions and temperatures, sometimes we also see a more complex meteorological map with information about air pressure and temperature or a satellite image that shows the cloudiness. In the further course of the day, when preparing breakfast, we see the nutritional facts on the packages depicted in small diagrams, for example as pie charts. On the way to the bus stop, a road sign shows us the detour that is necessary due to the road works. During the bus ride, we read the newspaper. It depicts the results of the latest elections in schematic maps; another article illustrates the mechanisms of action of soil fertilizers through an information graphic. During school or work, we use visual representations in various ways. And in the evening, we fix up a new shelf by consulting an instruction that visualizes all necessary steps in tiny little drawings. In short, throughout the whole day, we are confronted with information presented in form of visual representations, even if we are not data scientists or statisticians. Some of these visual representations are presented on paper or other analogous displays, others are presented on digital displays ranging from small devices as smartphones to large responsive road signs.

Humans use visualizations to overcome challenges in information processing and information communication. Complex relations, theoretical concepts, units on a microscopic level as well as large geographical regions can hardly be perceived in their entirety. Sometimes they bear over a long temporal period - such as the soil fertilization - or spread over an area that cannot be overlooked from one standpoint – such as in the weather map. Or the contrary is the case: They happen in a blink of an eye, or they are too small to be visible to the naked eye. In other cases, they refer to abstract, theoretical concepts such as models in physics or the power of political parties. All these instances have in common that they defy visual perception. Thus, visualization techniques are used that represent the concepts in order to facilitate the processing and communication of information. Humans have always used signs in order to communicate. In the beginning, gestures and noises were used, then, pictures were drawn that depicted situations. These pictures evolved and formed writing systems with pictograms and finally our writing system with phonemes. As a relatively new symbol system, diagrams evolved (Schnotz, 2001).

The development of digital technologies such as personal computers or - more recently – smartphones allowed the use of these symbol systems with interactive functionalities. That means, users can individualize the visual representations according to their necessities and interest. They can, for example, select the relevant information or arrange the information to build new contexts. However, it is mostly unknown whether these interactive functionalities are used and how they influence what one gets from the visual representations. In other words, referring to the above-mentioned example, do we get a more holistic and unbiased view of the election results if we read the newspaper as a digital document with the option to customize the visual representations? Do we use the offered interactive functions, and do we benefit from it if we want to answer a specific question rather than getting a gist of the results? And how does the use of such interactive visual representations influence the way we handle similar, but non-interactive visual representations? These questions are the focus of the present work.

The following theoretical overview is structured in three sections. In the first section, I will introduce visual representations as a format to convey information. In this section I define information graphics as one type of visual representations. Further, I describe how certain characteristics of the visual representations can affect how it is understood and how the combination of more than one visual representation can further influence the understanding. This overview leads to the last part of the first section that suggests that not all visual representations are appropriate for all tasks. The second section is about interaction. I define the term interaction and introduce the concept of representation control as a specific type of interaction. Moreover, I suggest that interaction allows for executing epistemic actions that serve for offloading cognitive processing steps onto the visual representation. The third section is about the difference between task performance and learning.

Visual representations

In the introduction, various types of visual representations have been mentioned, for instance maps, satellite images, diagrams, information graphics, or drawings. All of them have in common that besides the information content itself, its spatial position in the visual representation is meaningful (Larkin & Simon, 1987; cf. diagrammatic representation). The organization of information entities based on their spatial position in the representation allows inferences on how these information entities are related to each other. For example, as the distance between two depicted cities in the weather map is smaller, the real distance between the cities is also shorter. Another example is the spatial order in which processes are depicted that informs about their temporal sequence.

According to Larkin and Simon (1987) this meaningfulness of the spatial position of information is a feature of diagrammatic representations. In diagrammatic representations, information is encoded through its position in a plane. They possess a two-dimensional data structure that preserves the topological and geometric relations between the depicted components. Larkin and Simon (1987) distinguish these diagrammatic representations from sentential representations. In sentential representations, information is conveyed in a single sequence just like in natural language. A similar distinction is promoted by Schnotz (2001, 2002; Schnotz & Bannert, 2003). He distinguishes descriptive from depictive representations. Descriptive representations consist of symbols that describe an object. They have an arbitrary structure and their relation to the represented object bases solely on conventions. The written word of an object´s name is an example for such a descriptive representation. A depictive representation by contrast, is associated with the represented object through common structural characteristics such as the spatial arrangement of its elements. Depictive representations consist of iconic signs. Physical models or a picture are examples for such depictive representations. Also McCrudden and Rapp (2017) did publish a similar distinction as Schnotz (2001). They distinguish two types of visual displays: semantic and pictorial visual displays. The main difference between the two types is in the conventions that they use for communicating information. Semantic displays use symbols, pictorial displays use images (Carney & Levin, 2002). To sum up, visual representations have been classified in two categories: either as representations that convey meaning by their spatial configuration or their resemblance to the represented object, or as representations that use symbols and a linear structure for conveying meaning such as text (Larkin & Simon, 1987; McCrudden & Rapp, 2017; Schnotz, 2001). The present dissertation has its focus more on the former type, although information graphics are not limited to that type of representations.

Information graphics. Information graphics (or in short infographics) - as one specific type of visual representations - consist of text, images and graphical means, that are combined to communicate information, data or knowledge effectively (Holsanova, Holmberg, & Holmqvist, 2009; Weber & Wenzel, 2013). The characteristics of these elements can vary in a large range. Text can consist of single key words but also of text paragraphs, the pictures can be of diverging realism, and graphical means range from simple arrows to interactive highlighting devices (Holsanova et al., 2009). These single elements are embedded in or attached to each other, forming a unit, the infographic. The function of an infographic is primarily to illustrate and clarify complex issues and relationships (Holsanova et al., 2009), thereby informing the user about a topic (Weber & Wenzel, 2013).

In media technology, three basic types of infographics are distinguished: *principle representations* describe complex causal relationships and cover the questions "what" and "how", often encouraging temporal inferences, *cartographic infographics* depict spaceoriented information, often encouraging relational inferences and *statistics charts* illustrate quantitative information and relations among subsets (Zwinger & Zeiller, 2016), thus often encouraging hierarchical inferences.

Data representation and extracted information. The definition of infographics shows how divers infographics can be. Thus, it seems obvious that not all types of infographics might be appropriate for all communication purposes (Bibby & Payne, 1993; Gilmore & Green, 1984; for an overview Parsons & Sedig, 2012). In various domains, empirical research has investigated the influence of representation variation on the conclusions that are drawn.

A large body of research has investigated the influence of surface characteristics. This research is not limited to psychological studies but has also been executed for instance in the cartographic community (e.g. Meihoefer, 1973; for an overview Koch, 1993; Montello, 2002) or in information visualization, a branch of computer science (e.g. Ellis & Dix, 2007; Hullman, 2014). Surface characteristics that were investigated include the degree of realism in representations, the size of symbols, or the type of diagram that is used. For instance, Hegarty and colleagues (Hegarty, Smallman, & Stull, 2012) investigated the influence of complex compared to simple geographical representations on the performance in an information extraction task. Complex displays – albeit preferred by some participants – do hurt performance regarding the response times and error rates. Similar results were found for the number of details that are depicted in representations. Simplified rather than detailed representations facilitate factual learning and information integration (Butcher, 2006). Users take task-relevant and task-irrelevant information into account when making inferences from infographics and thematic maps complicating the task solution (Canham & Hegarty, 2010). Increased photorealism and the resulting larger number of details also have an influence on the perceived data quality. Novice users infer higher quality of spatial data with increasing photorealism of the depictions of this data (Zanola, Fabrikant, & Çöltekin, 2009).

Further empirical results could also show that novices base their conclusions more on the surface structure of representations than on the underlying principles (e.g. Chi, Glaser, & Rees, 1981; Novick, Hurley, & Francis, 1999). These results stand in accordance with the assumption that novices possess mostly unconnected fragments of knowledge (”phenomenological primitives”) that they built as superficial interpretations of experiences (diSessa, 1988, 1993). In these superficial interpretations, surface characteristics are weighted more than the underlying structure. Bennett, Toms, and Woods (1993) investigated the influence of different representation types on information extraction either about high-level constraints (such as the relationships among several variables), or about low-level data (i.e. the values of individual variables). They found differences in adequacy of representation types that suggest that task solutions can be supported by the use of specific representations. A further study dealing with graphs indicated that users infer the type of data from the graphical format in which the data is presented (Zacks & Tversky, 1999). Line graphs are interpreted as trends whereas bar graphs are more often interpreted as discrete comparisons.

In addition to the presented research on surface characteristics, the influence of the spatial organization of information has been subject of investigation. For instance, locating items in a graphic display in close proximity to each other or within the same regions, or connecting them, led to an impression of grouping of these items (Yu, Xiao, Bemis, & Franconeri, 2019). In infographics, the information and its position are both relevant in order to interpret it correctly (Larkin & Simon, 1987; Winn, 1991). Especially in cartographic infographics that suggest relational inferences the spatial organization is important. Thereby, not only the single location of the specific information entity relative to the frame, but also the relations to the information that is depicted in the surrounding locations can be of relevance. The spatial organization suggests an association between components that are depicted close to each other (Winn, 1991; Winn, Li, & Schill, 1991). In consequence, also comparisons between information entities that are depicted close to each other may be facilitated or even suggested by the spatial organization.

Other comparisons between information entities that are depicted in different parts of the infographic, for instance two different maps, might be less obvious and more difficult and therefore less often drawn.

The effect of the positions of related information units was investigated intensively in the context of the cognitive load theory (Chandler & Sweller, 1991; Sweller, van Merrienboer, & Paas, 1998) as well as of the cognitive theory of multimedia learning (Mayer, 2005). Information that is depicted in text and picture that relate to each other is learned better if it is integrated into one representation, rather than depicted in two separate representations, that is in far distance or in two adjacent displays (Tarmizi & Sweller, 1988). This effect is known as the split-attention effect or the spatial contiguity effect. It is explained by additional cognitive resources that are necessary for search and integration processes of corresponding pieces of information. As resources are limited, these resources are missing for elaboration and knowledge transfer (Ayres & Sweller, 2014). Lower performance in disintegrated formats is the result. Additional studies using eye tracking demonstrated that users of multimedia learning material made fewer eye movements that connected the corresponding information units in split formats or even ignored whole information units (Holsanova et al., 2009; Johnson & Mayer, 2012). Also in visual comparison tasks, integrated presentation formats were found to be of advantage compared with disintegrated formats (Bauhoff, Huff, & Schwan, 2012; Hardiess, Gillner, & Mallot, 2008). With larger distances, the working memory is used more intensively.

Similar research questions as the one mentioned have also been investigated in cartography, however with the focus on the design of maps according to the human cognition (for an overview: Montello, 2002). During the 20th century, psychophysical approaches were applied in the cognitive map-design research in order to investigate the perception and cognitive consequences of the variations of cartographic symbols such as graduated circles or gray scales. The focus, however, lay on perception and therefore I do not go into detail about these studies.

Combination of representations. Besides the form of a single visual representation, also the combination of various visual representations has been a matter of investigation. Especially for the use of infographics it is important to understand the functions and influence of the combination of two or more representations as infographics consist of different representations. One theory that addresses the benefits of the use of multiple representations in advanced knowledge acquisition in complex and ill-structured domains is the cognitive flexibility theory (Spiro, Coulson, Feltovich, & Anderson, 1988). It highlights the importance of approaching a complex topic from various perspectives in order to construct the own knowledge in a flexible way, preventing from oversimplification and biases. Perspective in this context is not restricted to the viewing angle on the represented content but refers to the way something is regarded. Spiro and colleagues (1988) focus on hypertext learning environments, in later publications (e.g. Spiro & Jehng, 1990, p.163) they call it "random access media" characterizing that the theory is not restricted to text and the access is not predicted in a linear way. The cognitive flexibility theory, however, does not define the type of the representations as well as their interplay in detail. Other theories and taxonomies have focused more on these issues (Ainsworth, 1999, 2006; Mayer, 2005). Mayer (2005) focuses in his cognitive theory of multimedia learning on the combination of text and pictures when learning, whereas Ainsworth (1999, 2006) developed a taxonomy of the functions that multiple external representations can have.

The cognitive theory of multimedia learning (CTML) describes how multi-media learning material is processed (Mayer, 2005). According to the theory, learning content that is presented in pictures and words is processed in two different channels that are distinguished on a sensory level by the modality that is involved in information acquisition, and on the level of working memory by the representational codes (verbal vs. pictorial). The two channels are assumed to have limited processing capacity. The information that is processed in the two channels is organized in two separate mental models that are integrated in a last step of processing into an integrated model that also involves prior knowledge. In the context of the CTML, a number of design principles for multi-media learning material were developed. Two of these principles that were also relevant for the present studies are the spatial contiguity principle and the coherence principle (Mayer & Fiorella, 2005). The spatial contiguity principle states that people learn better when corresponding text and pictures are presented close to each other rather than far from each other. The coherence principle states that people learn better when extraneous material (i.e. material that is not goal-relevant for the learning task) is excluded rather than included. That means, only the relevant information should be included in learning displays.

Whereas the CTML provides a model of the cognitive processing of multi-media material, Ainsworth (1999, 2006) focused more on the interplay between multiple external representations (MERs) and developed a taxonomy. She described and systemized the functions that multiple representations can have and thus explored another aspect of the combination of multiple representations more in depth. Ainsworth classifies MERs according to their functions in three categories: The first category consists of MERs with complementary roles that can either support complementary processes or provide complementary information. The second category consists of MERs that constrain interpretation. They are either composed of a familiar representation that constrains the interpretation of an unfamiliar representation or they are composed of multiple representations that restrict the interpretational options by their inherent characteristics. The third category of MERs constructs deeper understanding by supporting abstraction or extension or by illustrating how representations are related. With the distinction between these three functions of MERs, Ainsworth works out that multiple representations can serve a variety of functions and she suggests how to support these different functions by design characteristics. In the following studies, MERs of the first category were used: The infographic consisted of two maps that provided complementary information. Both maps had the same structure but depicted the election results for different types of votes and of different election periods.

Task-suitability of representations. The previous paragraphs showed that the strategic use of representation formats can facilitate information extraction or learning and that the use of combinations of multiple representations can further support these processes. When representations are used for information communication, two aspects are of special interest. First, as the design of representations suggests a certain interpretation, the risk of biased information communication is high. The designer of an infographic can intentionally use a representation format that suggests an interpretation of the data in favor of his opinion without indicating that the data might be interpreted differently when represented in another format. Second, the users´ aims are not known or they are so divers that it is difficult to address all at once. In order to select the type of representation or combination that is advantageous for a specific task, it is necessary to know what task is to be performed with the specific external representations. When infographics are used in informal learning environments or print media such as magazines or newspapers, there might exist a whole range of tasks or interests that potential readers can have. This makes it practically impossible for the designers of such infographics to meet the interests of all readers and adjust the representations accordingly. Either, they include only the information that is relevant for one specific task and thus optimize the representation for this specific task, maximizing the ease of use of the representation, but limiting its usefulness to one specific task; or they include more information and thus maximize the usefulness of the representation for a larger rage of tasks, but reduce its ease of use. Thus, there exists a trade-off between the usefulness, and the ease of use of a static infographic (see also Locoro, Cabitza, Actis-Grosso, & Batini, 2017).

In order to overcome these challenges, various representations could be presented, and the user could select the representation she considers the most adequate for answering her specific question. This relieves the user from the task to cognitively reorganize the infographic and to ignore the irrelevant information. However, it requires that the user is equipped with (meta-) representational competence (diSessa, 2004; diSessa & Sherin, 2000; Kozma & Russell, 1997; Novick et al., 1999). That means, the users need to know which representation is the most appropriate for a specific problem or question and they have to select from a variety of representations. There exist empirical studies that question the ability of problem-solvers to choose the adequate representation in order to facilitate problem solving (Hegarty et al., 2012; Vessey & Galletta, 1991). However, other studies showed that at least college students possess knowledge about the suitability of different forms of diagrams for problem solving tasks (Novick et al., 1999). Taken together, it remains an open question whether users of representations possess the competence to decide what representation is the most appropriate for an actual task.

Interaction

Apart from selecting the most adequate representation, another option is to offer the user the opportunity to interactively adjust the representation to the individual requirements by changing its content and its format. This means, the user obtains the information in form of an interactive infographic. However, a common definition of what the term “interactive” and the nouns “interactivity” and “interaction”[1] mean is missing. This lack of consensus could be a consequence of the different disciplines that are concerned with interaction. From a sociological perspective, interaction is investigated in terms of human communication. This approach is extended in mass-communication disciplines to computer-mediated human communication. In contrast, in computer science, interaction is investigated in the context of human-computer

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[1] I use the terms „interactivity“ and „interaction“ as synonyms, whenever endeavors have been made to differentiate between interactivity and interaction (e.g. Janlert & Stolterman, 2017; Quiring & Schweiger, 2008).

communication (Domagk, Schwartz, & Plass, 2010, see also Quiring & Schweiger, 2008). Being aware of the different research bodies investigating interaction, it seems reasonable that there exist various approaches to define or categorize interaction (e.g. Dix & Ellis, 1998; Yi, Kang, Stasko, & Jacko, 2007). One minimal definition in the field of interactive visualizations is that the term interaction can be seen "related to the activities that go on between a human and an artifact" (Janlert & Stolterman, 2017, p.113). That means the term interaction requires two conditions: (a) at least two participants – humans or non-humans – that must interact with each other, and (b) these actions must be reciprocal (Domagk et al., 2010). Parsons and Sedig (2011, 2012) also highlight the necessity of the involvement of two parties and define interaction as consisting of two components, the action of a user and the reaction of a system. In our case, the system consists of an infographic; that means, the user acts upon an infographic and receives responses in terms of changes in and of the representations in the infographic.

Beside these minimal definitions, interactivity still is a manifold concept without a common definition throughout the different disciplines (Sedig, Parsons, Dittmer, & Haworth, 2014). Therefore, various frameworks exist that aim to characterize interactivity in more detail. In media technology for instance, Zwinger & Zeiller (2016) classify infographics according to five features of interactivity: the degree of interactivity, course of action, communicative intent, communicative function through W-questions, and topic.

Regarding the first feature, they distinguish three different levels of interactivity. Low interactivity allows the user to navigate within the infographic and select content, thereby not changing the infographic. A middle level of interactivity allows the user to manipulate the infographic in form of interaction menus or sliders. High interactivity allows the user to interact with the data and the infographic, for instance filtering data (Weber & Wenzel, 2013). Also, the course of action is categorized in three types: In linear interactivity, the sequence of presentation is predetermined. The users can only decide how long they engage with the individual steps of the linear course, for instance through start/stop or forward/backward buttons. Non-linear interactivity provides the user the option to explore the infographic freely as it does not possess prescribed navigation paths. The third type, linear-nonlinear interactivity is a hybrid of both former types. It possesses a predefined path, additionally allowing the user to modify the infographic up to a certain degree. An example for a tool that allows this linear-nonlinear form is an integrated interaction menu that offers predefined options.

According to Zwinger & Zeiller (2016) four communicative intents of interactive infographics can be distinguished. The communicative intent can be (a) narrative, that means telling stories; (b) instructive, that is explaining and visualizing procedures and events; (c) explorative, thus giving the users the option to discover the depicted information by themselves; or (d) simulative, giving the users the option to experience the depicted process themselves. Additionally, the communicative function can be described using the W-questions what/who, when, where, how, why, how much. Last, they classified interactive infographics according to their topic. For this purpose, they used the editorial departments of a newspaper as the categories: Politics/Economics, Accidents/Natural disaster, Consumption, Sports, Science/Society, Crime, Others. This scheme serves for describing a given interactive infographic and analyzing it according to various characteristics.

A related concept of interaction is proposed by Roth (2011) when investigating cartographic interaction that is defined as “dialogue between a human and a map mediated through a computing device” (Roth, 2011 p. 14). He also prompts six fundamental questions about cartographic interaction (Roth, 2011, 2013b): *What* is cartographic interaction? What purpose is it used for and what values does it provide? (*why*?). *When* is it useful? *Who* are the users who benefit from its use? *Where* (i.e. on which devices) is it reasonable to use interaction? *How* should cartographic interaction be implemented? Cartographers approach these questions by theoretical considerations and empirical studies. So far, these studies often include qualitative data such as expert interviews or behavioral data from small sample sizes as in a card sorting task or interaction analyses with test users (Roth, 2011). The main focus of research on cartographic interaction is on designing interactive maps that allow for a simple use. Thereby, techniques of user-centered design are used when developing a specific cartographic interface.

By contrast, Kalyuga´s (2007) scheme of interaction aims more on classifying various interactive e-learning environments into a few categories. Based on Scheiter and Gerjets (2007), he distinguishes between three controlling characteristics that are subsumed under the term “learner control”: Control of information delivery (i.e. pacing and sequencing), control of representational forms (e.g. modality), and control of content (i.e. the amount of information, segmenting into units and selection of units). Moreover, he classifies interactive environments according to two dimensions of the responses of the environment: flexibility and dependence on previous activities of the user. On both dimensions, he distinguishes two manifestations, resulting in four different forms of responses. The responses could be (a) predetermined and independent of the user´s behavior; (b) flexible and independent of the user´s action; (c) adapted to the user´s prior behavior with a fixed set of options; or (d) iteratively adapted to the user´s behavior with a flexible set of options (Kalyuga, 2007). Associated with these four different forms of responses, Kalyuga also distinguishes four levels of interactivity. The feedback level is defined as the lowest level of interactivity and associated with predefined feedback on learner´s actions. A learner can for instance require information whether his or her solution steps have been correct. The manipulation level provides flexible responses, that are not adapted to the previous user´s behavior. On this level, transformations of the environment are immediately executed following a user´s action, often allowing learner control. An example is the rotation of an object in the environment through mouse movements or specifying input parameters for simulations. The adaptation level of interactivity involves responses of the system that are tailored to the user´s previous behavior. These responses are part of a predefined set of possible responses. For example, the following learning task is selected from a pool of predefined tasks, based on the user´s responses to the previous tasks. On this level, also learner control as well as system control is possible. The highest level of interactivity - the communication level – involves flexible responses of an online environment that are iteratively adapted to the actions of the user. Kalyuga describes this level as requiring communication channels between the users, in the case of an e-learning environment these users would be the learners and the instructors.

To sum up, despite some differences in the definition of interactivity, there exists an overlap between the different branches of research on various characteristics of interactivity.

In all these definitions, interaction requires reciprocal actions between the user and a system. Thereby, interaction is seen as ranging on a continuum or between different levels, that means that there exists more than interactive and noninteractive, but some systems can be classified as more interactive than others.

Representation control. One specific type of interactivity is representation control. As in Kalyuga´s (2007) distinction between the three controlling characteristics of learner control, representation control allows the user to select the form in which the information is presented. However, my understanding of representation control is broader: representation control also allows the user to vary the content that is depicted by selecting from a predefined set of variables. Thus, I define representation control as the ability to alter the form of presentation of the displayed information in order to adjust it to the task requirements, including the selection of content from a predefined set. Representation control in the presented studies allows the user to execute spatial transformations and the selection of information in the external visual representation.

Both functions of representation control are based on well-studied principles of cognitive processing of multimedia (Kirsh, 1995; Mayer, 2005; Mayer & Fiorella, 2005; McCrudden & Rapp, 2017; Moreno & Mayer, 1999; Mwangi & Sweller, 1998). Additionally, they have already been incorporated in design advices for practitioners (Bertin, 1967; Tufte, 1983).

The first interactive function, the spatial reorganization[2], allowed the user to rearrange the given information in the infographic. In the presented studies, the information was depicted in two maps that were presented side by side. With the option to spatially reorganize the infographic, the user could select how the information was distributed among the two maps. This function aimed at minimizing the split-attention effect, that is the impaired learning from separate sources due to the need to mentally integrate information of these sources (Chandler & Sweller, 1991; Sweller, Chandler, Tierney, & Cooper, 1990; Tarmizi & Sweller, 1988). The same effect has been described as spatial contiguity principle in multimedia learning (Mayer & Fiorella, 2005; Moreno & Mayer, 1999, 2000). It states that learning is enhanced when printed text and pictures are physically integrated or close to each other rather than physically separated. The task in our study was not about learning from text and pictures but about extracting and comparing information from two maps that were part of an infographic. However, the process of extracting and mentally integrating information that relates to each other is still the same.

The other interactive function, the selection of information[3], allowed the user to choose what information is depicted in the infographic by selecting it on checker boxes in an interaction menu. With this option, the user could reduce information density in the infographic and thus facilitate cognitive processing. This function follows the coherence principle that states that adding words or pictures to a multimedia presentation decreases the performance on tests of retention or transfer (Mayer, 2014; Mayer & Fiorella, 2005; Moreno & Mayer, 2000). Both interactive functions were also considered as cartographic interaction primitives by Roth (2011, 2013a, called “arrange” and “filter”).

With regard to the classification of interactivity by Zwinger and Zeiller (2016), the functions of representation control can be classified as providing a middle degree of

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[2] McCrudden & Rapp (2017) call this function localization.

[3] McCrudden & Rapp (2017) call this function extraction.

interactivity. The infographic allowed the user to select information and to reorganize the spatial arrangement through an interaction menu (i.e. representation control). Regarding the course of action, the infographics did not prescribe the order of presentations and as such were nonlinear in nature. The infographics used in the present studies had an explorative communicative intent as they allowed the user to explore a topic and extract information that they considered to be relevant. The topic of the infographics fell in the category Politics/Economics, depicting the fictitious results of political elections.

Epistemic action - cognitive offloading. Representation control allows the user to offload covert processing steps from working memory by turning them into overt actions in the environment. These overt physical actions serve a cognitive function and can be classified as epistemic actions (Kirsh & Maglio, 1994; Parsons & Sedig, 2011). These epistemic actions replace the cognitive processing steps that otherwise would require anticipating the results of a transformation mentally, thus externalize them into the environment. This externalization of processing steps through overt actions is the key process of cognitive offloading, which allows for overcoming the internal limitations of information processing and memory capacity (Baddeley, 1986; Clark, 2008; Miller, 1956; Risko & Gilbert, 2016). This "use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand" (Risko & Gilbert, 2016, p. 676) can result in offloading into the external environment or into the own body. In the present studies, I focus on the former type of externalization into the external environment, the latter one is investigated under the term embodied cognition (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001) and not subject of this dissertation. The offloading into the external environment often bases on the fact that the mere presence of an external representation facilitates or reduces the cognitive processing (Scaife & Rogers, 1996).

Interactive visual representations are also a matter of investigation in information visualization research, a branch of computer science. Liu and Stasko (2010), two computer scientists, identified three aims that physical actions on data visualizations can have. The three aims are external anchoring for coupling of internal and external representations, information foraging, and cognitive offloading of memory. Regarding external anchoring, reasoning is often facilitated if mental concepts can be attributed to external representations. Therefore, people project their mental concepts on external representations or try to locate appropriate external anchors for their ideas. People additionally often restructure and explore data visualizations in order to gather new or additional information (i.e. information foraging). As new insights are gained, people create external representations in which the insights are stored. Additionally, they can save the actual state of whole visualizations in order to retain large information units (i.e. cognitive offloading). Taken together, Stasko and Liu (2010) further distinguished between the three aims of physical actions on data visualizations that were subsumed under the term cognitive offloading by other researchers (Risko & Gilbert, 2016).

The cognitive offloading processes, however, are not restricted to memory representations (Risko, Medimorec, Chisholm, & Kingstone, 2014). Cognitive offloading can also encompass physical transformations in order to avoid corresponding mental operations such as mental rotation. In a study investigating the use of interactive functions during a Tetris game, Kirsh and Maglio (1994) describe that the gamers often rotate the blocks through the rotation function (i.e. execute a motoric action that leads to a manipulation of the external environment) instead of simulating the outcome of the rotation mentally. However, the rotation of Tetris blocks is a distinct function that only allows to select the direction of rotation. In more complex representations such as infographics, the degrees of freedom to adjust a representation to the task requirements are more divers. Thus, more complex representations might also impose more and other requirements to the users than the Tetris game or other simpler representations did. Such requirements are the knowledge about the exact type and organization of the required information, about the task structure, and about the strategy how to achieve an optimal information representation. Therefore, it is unclear whether such cognitive offloading processes are used with more complex representations that also have semantic meaning.

In the present studies, I investigated whether users of complex graphical representations - in the form of infographics - use the strategy to cognitively offload mental transformations through the use of interactive functions that were provided with the infographics. In the investigated tasks, successful offloading of cognitive processes involves the adaptation of the depicted information to the actual task requirements. Such adaptations of the depicted information are enabled through representation control (Scheiter, 2014; Scheiter & Gerjets, 2007). Representation control allowed the user to a) change the spatial organization of the depicted information resulting in positioning relating information in close proximity and clustering information units and resulting clusters and b) (de-)select information units according to their relevance for the task changing their visibility. Thus, representation control allows cognitive offloading in interactive infographics through adaptations of the depicted information.

Task performance vs. procedural learning

As shown in the previous section, there exists some evidence that cognitive offloading can support task performance. However, there exists also some evidence that cognitive offloading hinders learning (e.g. van Nimwegen & van Oostendorp, 2009). One field in which this effect was investigated is wayfinding. A consistent result in this field is that route knowledge is acquired to a lower degree if navigational aids, for instance turn-by-turn auditory instructions, are used (Fenech, Drews, & Bakdash, 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Gardony, Brunyé, & Taylor, 2015). Similar results were also found for skill retention and procedural knowledge. Skills and procedural knowledge are often offloaded to automated processes in aviation, medical or military contexts. That means, during qualification, pilots, medical or military personnel practice skills and procedures that they do not execute in their daily routines but offload to machines. In emergency situations however, they suddenly are required to execute these skills and procedures without external support by machines. Various studies have shown that increasing automation results in lower skills (e.g. Casner, Geven, Recker, & Schooler, 2014; Ebbatson, Harris, Huddlestone, & Sears, 2010). These results suggest that immediate task performance and subsequent execution of procedures or skills, including their learning and retention, should be distinguished from each other.

A theory that offers such a distinction between the immediate task performance - that at the same time serves for acquiring and training new skills and knowledge (i.e. the practice or learning phase) - and subsequent long-term competence is the desirable difficulties approach (Bjork, 1994; Schmidt & Bjork, 1992). It states that learners often benefit from a more demanding learning phase in subsequent tasks although they initially show low performance. High performance in the learning phase by contrast, does not necessarily imply that insights and skills are acquired (for a review: Soderstrom & Bjork, 2015). According to this approach, providing representation control and thus allowing cognitive offloading might be advantageous for the immediate task performance. However, for procedural learning and skill retention, representation control might be detrimental. The concept of desirable difficulties was developed and investigated in the context of explicit learning (e.g. Yue, Bjork, & Bjork, 2013). However, it might also apply to incidental learning environments in which knowledge is acquired in response to exposure to a specific content without the explicit intention to learn (Marsick & Watkins, 2001). Taken together, the desirable difficulties approach suggests that cognitive offloading might impair performance in a subsequent task that does no longer provide cognitive offloading options.

Another model that distinguishes between various phases when executing a task stems from Salomon and Perkins (2005). They distinguish three effects of the use of technology for task performance: the immediate effect with technology, the subsequent effect of technology and the profound long-term effect through technology. Effects with technology refer to changes in intellectual performance during the use of technology (e.g., cognitive offloading or epistemic actions), effects of technology refer to changes in cognitive performance after the use of technology (i.e. without the tool). The effect through technology refers to the fundamental reorganization of performance through technology (i.e. also without the tool). Effects with technology in this framework represent the potential benefits of representation control in the learning phase, whereas effects of technology represent the acquired knowledge and skills that are used subsequently. Salomon (1974, 1979, 1990) investigated the influence of technology on learning. In his research, media is used to model cognitive operations and processing steps that are required when solving a given task. This modeling allows the users to internalize the required steps and improve in subsequent similar tasks. Cognitive operations and processing steps are made explicit, demonstrating the underlying task structure and thus facilitating knowledge acquisition and task solving. Contrary to the desirable difficulties approach, it is assumed that the explicit modeling of the processing steps frees cognitive resources that might be available for deeper and more elaborate processing, resulting in enhanced learning (Salomon, 1990; Sweller et al., 1998). Though, whether the additional cognitive resources are available for deeper and more elaborate processing or not, depends on the costs that come along with the planning and the execution of the externalization of the processing steps. If the costs for planning and execution outweigh the freed cognitive resources, cognitive offloading can even hinder learning and comprehension (Lunts, 2002; Scheiter, 2014; Scheiter & Gerjets, 2007; Schnotz & Rasch, 2005).

In sum, offering users representation control - that means the possibility to reorganize a visual representation or to select its content and thus to adjust it to the actual task requirements – allows them to execute epistemic actions. Representation control serves the purpose of externalizing mental processing steps from working memory into the external visual representation allowing the user to solve the task more efficiently. According to Salomon and

Perkins (2005), representation control can support learning to solve a specific task in two ways. The first way is that through representation control the individual processing steps can be made explicit. That means, representation control might enhance procedural learning and task performance if it supports the user to internalize the overt processing steps into corresponding mental processing steps (Salomon, 1994). As such, representation control serves a modeling function (Bandura, Ross, & Ross, 1961). The second way is that through the use of representation control, the task can be simplified. Its solution requires less cognitive resources. The freed resources might be used for analyzing and understanding the underlying task structure. In both ways, representation control should benefit procedural learning and subsequent task performance contrary to the prediction of the desirable difficulties approach. The present dissertation had the aim to investigate the use of representation control and its influence on task performance and procedural learning. Especially whether representation control benefits or hinders procedural learning.

Overview of the studies

From the previous theoretical overview, I derived three major hypotheses. Based on the research on cognitive offloading of processing steps like mental rotation, I expected that the participants use representation control in a strategic way in order to adjust the infographics to the task requirements. Thus, the option to use representation control should have a positive effect on the immediate task performance as it alleviates the mental effort and reduced the number of processing steps that are necessary for solving the task.

According to the desirable difficulties approach, representation control should have a positive effect on the immediate task performance especially regarding the time on task, but it should detriment the performance in a subsequent task that no longer offers the use of representation control. Learning is encouraged with difficulties that are included in the learning phase. As representation control achieves the contrary, namely a facilitated task solution during the learning phase, it might be dysfunctional for learning.

To the contrary, according to the approach by Salomon, representation control should benefit both, the task solution as well as learning. Externalizing the solution steps serves two functions. First, it frees cognitive resources that might be used for learning, and second, the external execution of the adjustments serves as modeling. Modeling is known as a strategy that supports procedural learning (Bandura et al., 1961).

In order to test these hypotheses, I conducted three studies with five experiments that are shortly described in the following section. These studies had the objective to investigate the influence of representation control in infographics on the immediate task performance and the learning for subsequent tasks. Thereby, two different tasks were used: a goal-free task (Study 1) and a task that required the extraction of specific information (Study 2 and 3). Additionally, in Study 3, I varied the delay between the practice phase and the testing phase among the experiments. In the last experiment of Study 3, I additionally manipulated the degree of automation of representation control. Table 1 depicts an overview of the studies. The specifications of all variations are provided in the experimental descriptions.

Two of the three studies are published as part of two journal articles. Study 2 is published in Plos One as a single study paper (Moritz, Meyerhoff, Meyer-Dernbecher, & Schwan, 2018; see Appendix B), Study 3 contains three experiments and is published as online first article in the Journal of Educational Psychology (Moritz, Meyerhoff, & Schwan, 2019; see Appendix C). Study 1 that consists of one experiment is not published so far (Appendix A).

Table 1: Overview of the studies

Study	Experiment	Type of Task	Performance Measure	Testing Phase	Conditions
1		goal-free information extraction	task performance	-	• representation control ○ with instruction ○ without instruction • no representation control
2		specific information extraction	task performance	-	• representation control • no representation control
3	1	specific information extraction	task performance learning	immediate	• representation control • no representation control • baseline
3	2	specific information extraction	task performance learning	delayed	• rc – rc • no rc – no rc • rc – no rc • no rc – rc
3	3	specific information extraction	task performance learning	immediate	• representation control ○ active ○ modeling ○ short-circuit • no representation control

Note. rc = representation control

Infographics

As I used the same infographics in all studies, the following section will give a general description of these infographics. Specificities of the infographics in single experiments are mentioned in the individual experimental description. All studies were conducted with cartographic infographics that showed election results for a fictitious country (see Fig. 1 for an example). The infographics consisted of two thematic maps that were arranged side-by-side. Both maps depicted the same fictitious country consisting of 18 districts. In each infographic, information about two types of votes for two consecutive election periods was shown. The two types of votes were called first and second vote inspired by the German election system. Two colored bars indicated the winner's party in all districts (see Fig. 1). Half of the infographics were initially organized by the type of votes (i.e., the first votes on the left side and the second votes on the right side; Fig. 1a). The remaining half of the infographics were organized by election period at the beginning of the trial (i.e., the 2009 election on the left side and the 2013 election on the right side; Fig. 1b). The experimental design, that means whether the spatial organization varied between participants or within participants differed between the experiments.

The option to use representation control differed between participants. The participants in the conditions with representation control could reorganize the infographic (i.e., change the spatial organization of the information in the maps) or reduce information density (i.e., select which information is depicted) though the corresponding menu on the left side of the infographic. This menu was not present or grayed out and inactive in the conditions without representation control. The type of task that had to be accomplished with the infographics differed among the studies. Thus, it is described in the study description.

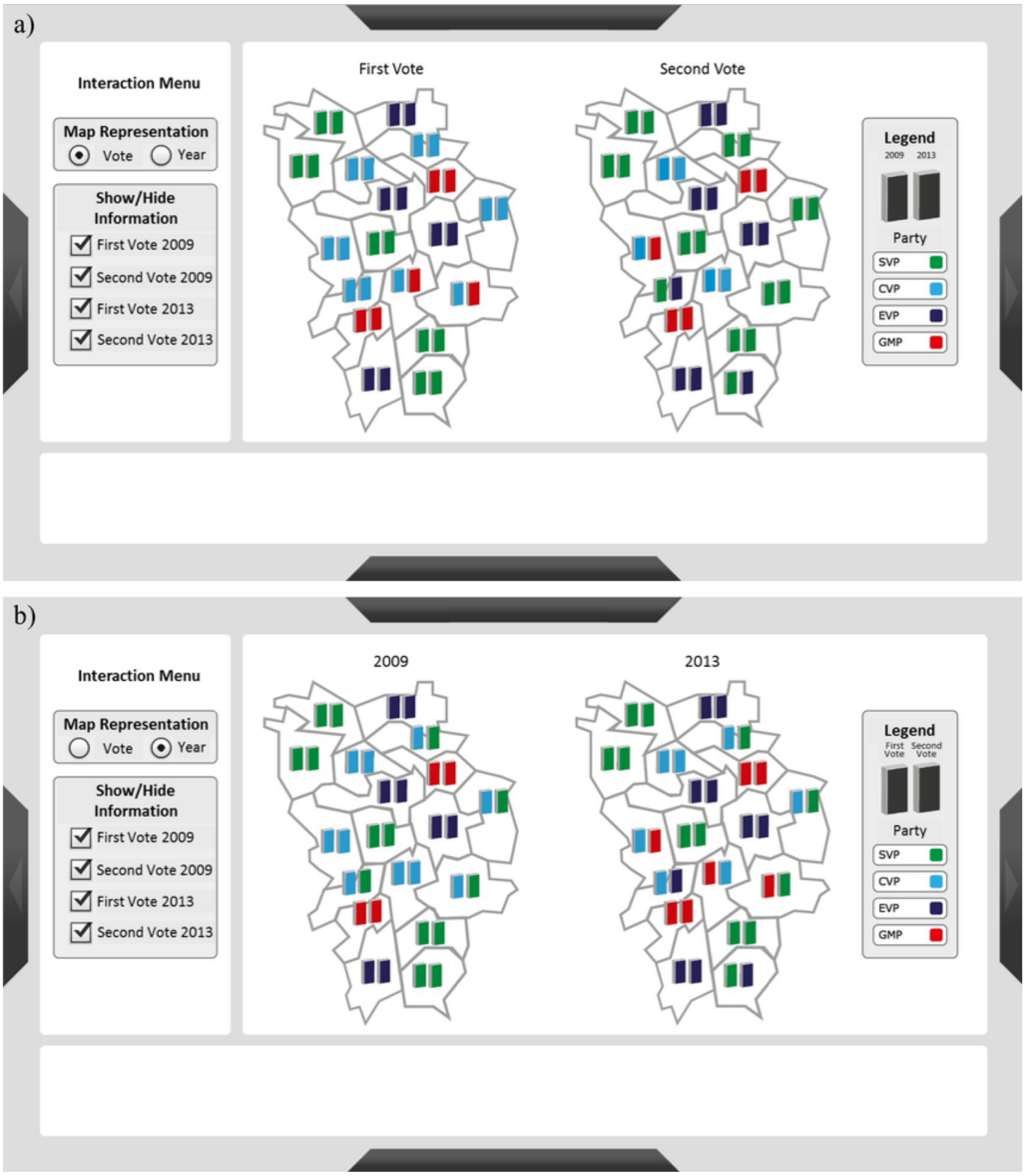

Figure 1. Illustration of the infographics used in all three studies. The maps were initially organized (a) by type of vote or (b) by election period. Interactive reorganization was possible only in the conditions with representation control. Only in these conditions, the interaction menu (left) was active.

Study 1

The aim of Study 1 was to investigate whether and how representation control and the spatial organization influence the conclusions that are read off from an infographic. In detail, I investigated the number and type of statements that were made depending on the option to reorganize and select the depicted information. Additionally, I investigated whether the participants needed an explicit instruction for the representation control features in order to use them.

In this study, the participants received only one infographic and were asked to formulate statements about the depicted data. The goal was to gather as much correct information as possible during the task phase that lasted 40 minutes. The focus in this study was on the comparison of information units. Whenever more than one information of the infographic was mentioned in a statement, it was categorized as a match or a mismatch statement. A match statement contained information that was originally depicted in one map, whereas a mismatch statement contained information that was spread over both maps in the original organization.

I designed three conditions. In the condition with representation control with instruction, the participants could change the spatial organization of the information or select information. Importantly, they were instructed how to use these features. I compared this condition with two other conditions. In the representation control condition without instruction, the functionalities of representation control were available but not explicitly explained in the instruction. In the no representation control condition, representation control was not available to the participants, that means they could not change the infographic at all.

I had three hypotheses in this study. First, groups with representation control use the option to reorganize and select information strategically in order to facilitate the information extraction task. Thus, these groups are expected to use representation control at least once. Second, as the mental effort that has to be invested for comparing information in two maps is larger, the group without representation control is expected to produce fewer comparison statements than the groups with representation control. Third, through representation control the spatial organization can be changed. That means, comparisons between information units that are originally depicted side-by-side and comparisons between information units that are originally depicted in two separate maps should occur equally often, whereas in the group without representation control, the comparisons should more often reflect the original spatial organization.

Consistent with Hypothesis 1, participants who had the option to change the infographic interactively used this option. Irrespective of whether they were instructed on the usage of the interactive functions or not, they used these functions equally often. Regarding the additional aim of Study 1 to investigate the effects of the availability of representation control on the statements produced, no effects were found. The overall number of statements was comparable among all three conditions. Also, the proportion of comparisons that contained information from both maps to comparisons that contained information only from one map was constant across the three groups with a preference for the latter type of comparison. It seems that the availability of representation control did not influence the information that was extracted from the infographic.

This first study demonstrated that people used interactive functions when they were exploring infographics. This is in accordance with research on the acceptance and the actual use of interactive infographics in real newspapers (Zwinger, Langer, & Zeiller, 2017; Zwinger & Zeiller, 2017). Zwinger and colleagues found in an online survey that most readers of online newspapers reported to use the option to interactively manipulate infographics at least moderately intensive. The findings of Study 1 are also consistent with the results of prior studies that showed that people who were learning with videos used the offered interactive features such as stopping or browsing (Merkt, Weigand, Heier, & Schwan, 2011; Schwan & Riempp, 2004). However, in my study, the availability of representation control did not influence the extracted information. One possible reason for this might be the task. The participants were asked to read off information from the infographic without giving them a specific question that should be answered. That means, they were confronted with a goal-free task (Ayres, 1993; Sweller & Levine, 1982). It is known that in goal-free tasks the cognitive load is reduced as there exists no goal that has to be held in memory during the individual steps of solving the task. This relatively low cognitive load induced by the goal-free character of the task might have reduced the benefit of the option to offload cognitive processing steps onto the infographic. The benefit of cognitive offloading was previously demonstrated in tasks with specific goals (Kirsh & Maglio, 1994). That means, even if there was no difference in the information that was extracted from the infographic in the present study, representation control might influence performance in tasks with specific goals. Thus, in the following studies, I investigated the influence of representation control on the performance in tasks with specific goals.

Study 2

The aim of Study 2 was to investigate how representation control influences the performance in an information extraction task with a specific goal. In detail, I investigated whether participant used the option to reorganize and select information (i.e. representation control) in an infographic when answering a predefined question. Further, the influence of representation control on the performance, in this case the time on task and the proportion correct, were subject of investigation in this study.

The participants received 24 infographics with one question each. The infographics depicted the information in two maps as described above. In half of the trials, the information was organized by type of vote, in the other half of the trials, the information was organized by election period. This organization was varied within participants. They were asked to answer questions like “In how many election districts did the party SVP gain the majority of first votes in both 2009 and 2013?” with the aid of the infographic. This question focused on a comparison of the first votes between the two election periods. In contrast, the question, “In how many election districts did party SVP gain the majority of first and second votes in 2009?” focused on a comparison between the types of vote for one election period. The relevant information for answering the questions was either initially depicted side-by-side in one map (i.e. match trial) or distributed among the two maps of the infographic (i.e. mismatch trial). For instance, the first question comparing the election periods represents a match trail if it is presented with the infographic that is depicted in Figure 1a); however, it represents a mismatch trail if it is presented with Figure 1b). In contrast, with the second question it is the other way around. Importantly, the terms match and mismatch refer to the initial organization of the infographic at the beginning of a trial prior to any self-initiated changes in the spatial organization of the information.

The participants were divided in two groups. In the condition with representation control, the participants could change the spatial organization of the information or select information. In the condition without representation control, the static condition, the participants could not change the infographic at all.

I hypothesized that participants use representation control in a task-appropriate way when they have the option to do so. More specifically, this assumption led to four hypotheses. First, I expected the participants with representation control to use the option to reorganize the infographic when the spatial organization did not match the task requirements in order to establish a high spatial contiguity. Second, I expected the participants with representation control to deselect the irrelevant information and thereby increase the coherence of the depicted information. Third, I expected the participants with representation control to answer the given question faster than participants of the static condition when presented with an initially mismatching infographic. And fourth, I expected the participants with representation control to answer the given questions more often correctly than participants of the static condition.

Consistent with the first and second hypothesis, participants reorganized the depicted information more often in mismatch trials than in match trials and they used the option to select information equally often in match and mismatch trials. These results corroborate the assumption that participants use representation control strategically in order to offload mental processing. The result regarding the reorganization is conform with the spatial contiguity principle, the high rate of information selection (>70%) is in accordance with the coherence principle and former empirical results demonstrating a benefit of designs that are reduced to the relevant information (Canham & Hegarty, 2010). This result however contradicts other results that demonstrated a preference for complex representations (Hegarty, 2013; Hegarty et al., 2012; Hegarty, Smallman, Stull, & Canham, 2009). The benefit of representation control is further proved by the results regarding the participants´ performance. In line with the third and fourth hypothesis, participants who had the option to use representation control outperformed participants who only had the static infographics with respect to response time and accuracy. Especially in mismatch trials in which the relevant information for the question at hand was distributed across both maps, representation control was beneficial.

This second study provides evidence for the beneficial effects of offloading transformation processes when confronted with a task that has a specific goal (Risko & Gilbert, 2016). The mental anticipation of such transformations of representations are demanding and thus their externalization to the environment increases the performance. In this study, I conceptualized the use of representation control as an instance of cognitive offloading.

To sum up, the participants spontaneously used representation control for efficiently solving an information extraction task. Additionally, the availability of representation control improved response time and accuracy, especially when the relevant information was originally distributed among the maps (i.e. in mismatch trials).

Study 3

In Study 2, I could show that people use representation control, that is the option to adjust infographics to the requirements of a task with a specific goal. Through the use of representation control, they can offload cognitive processing steps and facilitate the task solution. However, it remained unclear whether the use of representation control also facilitates the acquisition of the relevant processing steps. This research question is subject of investigation in Study 3. Thus, the main goal of Study 3 was to investigate how the option to use representation control in a practice phase influences procedural learning measured as the performance in a testing phase without representation control. The participants solved the same information extraction tasks as in Study 2. I also explored the time on task as well as the proportion correct as measures of task performance and I analyzed how often participants used representation control when it was available. Study 3 consisted of three experiments. All three experiments had a two-phase design with a practice phase and a testing phase.

Experiment 1. The practice phase of Experiment 1 was comparable to Study 2. However, Experiment 1 extended Study 2 by an additional testing phase. This phase followed on the practice phase with a delay of 20 minutes. It consisted of 24 structurally equivalent tasks as in the practice phase. In Experiment 1, the participants did not receive representation control in this testing phase and thus had to execute the transformations of the infographic mentally. I compared the participants´ performance to a condition in which representation control was not available during both phases (no representation control condition). An additional control group that only solved the tasks of the testing phase allowed to measure the untrained performance in the testing phase (baseline condition).

For the practice phase, I expected to replicate the results of Study 2. In detail, the participants who had representation control available should outperform the participants without representation control. This benefit should be apparent especially in trials in which the spatial organization of the infographic and the task requirements did not match. For the testing phase, there were two possible outcomes conceivable. On the one hand, the participants with representation control in the practice phase could show an enhanced task performance also in the testing phase. This should occur if they internalized the necessary transformations that they had executed externally in the practice phase. On the other hand, the participants with representation control in the practice phase could show an impaired task performance in the testing phase compared with the no representation control condition. This should occur if they only learned how to use the functions of representation control rather than the underlying transformations.

In line with my hypothesis and the results of Study 2, the participants used representation control in the practice phase. This was more often the case in mismatch trials than in match trials. Participants who had representation control available performed better in the practice phase - both regarding response time and accuracy - than participants without representation control. Thus, representation control fostered problem solving. This result was also consistent with my hypothesis and replicated the findings of Study 2. However, in the testing phase, when representation control was no longer available, the beneficial effect of representation control vanished. Participants who could use representation control in the practice phase but not in the testing phase performed in mismatch trials on a comparable level with the baseline condition that was confronted with the task for the first time in the testing phase. The participants did not learn the underlying structure of the task when they had the option to offload the processing steps to the infographic in the practice phase. However, in match trials that were more often solved mentally without offloading the processing steps through the use of representation control, the participants of the representation control condition were able to solve the tasks faster and at the same level of accuracy than the untrained baseline condition. The same effect was visible in match and mismatch trials in the condition without representation control. Thus, the participants seem to learn the underlying task structure whenever they solved the task by mental processing rather than cognitive offloading. Thus, the first experiment of Study 3 could show that the beneficial effect of representation control did not extend to subsequent tasks that had to be solved without representation control. However, the time delay between the two phases was only 20 minutes and all tasks were structurally identical. Thus, in a further experiment I tested whether the results generalize to longer intervals between practice and testing and to near transfer tasks.

Experiment 2. The aim of the second experiment of Study 3 was to replicate the findings of Experiment 1 and to extend these findings regarding long-term effects and near transfer. Thus, the retention interval (i.e. the delay between the practice and the testing phase) lasted one day (i.e. 24 hours) and the tasks in the testing phase contained structurally identical (reproduction) as well as structurally similar (near transfer) problems as in the practice phase. The participants were presented only with one spatial organization of the infographic in the practice phase. Half of them got the organization by type of vote, the other half by election period. In the reproduction task of the testing phase, they got the same spatial organization of the infographics once again. In the near transfer task, however, the spatial organization of the infographics changed, and information was now organized by the other criterion. In the practice phase as well as in both tasks of the testing phase, half of the questions focused on a comparison between types of votes, the other half on a comparison between election period resulting in an equal number of match and mismatch trials.

An additional aim of the experiment was to rule out the alternative explanation that the benefit of the no representation control condition in the testing phase of Experiment 1 resulted from higher compatibility among the practice and the testing phase. Therefore, Experiment 2 consisted of four conditions in which the availability of representation control was crossed over the practice and the testing phase. That means, in this experiment, half of the participants could use representation control in the testing phase.

As the practice phase was similar to Study 2 and the one of Experiment 1 in Study 3, I had the same hypotheses as in these experiments: I expected a benefit of the group with representation control, especially in mismatch trials. For the testing phase, I also expected the results to coincide with the ones of Experiment 1, even with the extended retention interval of one day. The participants should learn only how to use representation control rather than the underlying principles. Thus, their performance should drop in both, in a reproduction as well as in a near transfer task, when they are confronted with the tasks without the option to use representation control.

Regarding the effects with representation control in the practice phase, also Experiment 2 of Study 3 replicated the results of Study 2. The participants used representation control, especially when the task requirements and the spatial organization of the infographic did not match (mismatch trials). Participants benefitted from the option to use representation control in all mismatch trials (in the practice as well as in the reproduction and transfer task of the testing phase): They showed a higher proportion correct and a shorter time on task than participants without representation control. Thus, representation control supported the immediate task performance in the information extraction task. A different result appeared when focusing on the effects of representation control on learning in the testing phase. Participants who could use representation control during the practice phase but not during the testing phase responded more slowly and with a lower proportion correct in the reproduction task than participants without representation control in the practice phase. This result is in accordance with the finding of Experiment 1. Participants with representation control in the practice phase did not learn the underlying task structure and thus, they suffered a drop of performance when solving the reproduction tasks without representation control.

The alternative explanation of the results of Experiment 1, a higher compatibility between the availability of representation control in the two phases, could be ruled out in Experiment 2. Both conditions with representation control in the testing phase did not differ in their performance in the testing phase despite a higher compatibility for the group that had representation control available in both phases. Besides the generalization of the results to a longer retention interval, Experiment 2 had also the aim to test a generalization of the results to a near transfer task that had a similar but not the identical surface organization. Experiment 2 showed that the results of the reproduction phase do not exactly generalize to a near transfer task. Both groups without representation control in the testing phase performed on a comparable level in the transfer task, irrelevant of the availability of representation control in the practice phase. The participants without representation control during practice failed to transfer their knowledge about solving the reproduction problems to transfer problems with a diverging spatial organization. This is line with previous research on the transfer of problem-solving skills (e.g. Catrambone & Holyoak, 1989).

In contrast to the two groups without representation control during testing, there was a difference between the two groups that had representation control available during testing: their interaction behavior differed. The participants without representation control during practice used the option to select information in the transfer task less often than participants who could already use this option during practice. This suggests that they learned the underlying task structure in the practice phase and thus did not rely on the information selection strategy when solving the transfer tasks of the testing phase.

To sum up, Experiment 2 extended the results of Experiment 1. It showed that the results for the reproduction task also hold for a longer retention interval of one day. Moreover, in the transfer task, participants without representation control in both phases failed to benefit from their previous experience. To the contrary, participants who had practiced without representation control used less often the option to reduce information, but still reached the same performance as participants who had practiced with representation control. Experiment 2 also showed that the detrimental effect of representation control on a following testing phase cannot be explained as a compatibility effect.

Experiment 3. The previous experiments investigated the effect with representation control on task performance, that means the influence of using representation control in a task, and the effect of representation control on learning, that means the influence of having used representation control in a previous task. However, possible explanations of the effects have not been subject of investigation. Thus, so far it was unknown why cognitive offloading through representation control did not benefit the learning of the relevant task structure. One option is that adjusting the infographic to the task requirements might not have served as a model for how to solve such tasks in general. When normally modeling a procedure, this procedure is depicted to the learner systematically in a stepwise way (Bandura, Ross, & Ross, 1961; Salomon, 1974). In the reported experiments however, the participants could reorganize and select information themselves. This was assumed to function as modeling. However, no modeling in the sense of the classic definition of demonstrating the procedure sequentially was used. Additionally, using representation control in order to offload mental processing steps also required cognitive resources for planning and executing the relevant steps of the adjustments that might have prevented the participants from learning the underlying task structure.

Based on Salomon´s (1974, 1994) distinction between a modeling and a short-circuit condition, I used different types of representation control that varied in the automation and in the explicitness of the particular steps of adjustment in Experiment 3. In detail, I compared three types of representation control: The active representation control condition was identical to the representation control condition in Study 2 and both experiments of Study 3. Participants could reorganize and restructure the infographic through selecting the individual steps of transformation. In the modeling condition, the participants could decide whether to adjust the infographic or not. The adjustment was then executed automatically, whereby all necessary steps were visible. The short-circuit condition was similar to the modeling condition, except that only the final state of the adjustment was depicted without the intermediate steps. In an additional baseline condition, the participants only completed the testing phase. The design of the experiment followed the design of Experiment 1. Thus, the different types of representation control were only available in the practice phase. In the testing phase, which followed 20 minutes after finishing the practice phase, the participants were not allowed to use any type of representation control. In line with the previous experiments, I analyzed the time on task as well as the proportion correct in both phases. For the practice phase, I also analyzed the use of the interactive features in all three conditions.

For the practice phase, I expected to find an increasing performance with an increasing level of automatization, resulting in the highest performance in the short-circuit condition, followed by the modeling condition and the lowest performance in the active representation control condition. The lowest performance of the active representation control condition should be caused by the higher cognitive requirements of the offloading process. In the active representation control condition, planning and executing the individual steps was still necessary - although they could be executed externally - whereas in the other two conditions only the decision whether to adjust the infographic was required.

For the testing phase, however, I expected to find another pattern of results. The participants of the modeling condition should outperform the other participants. In the modeling condition, the participants did not need to plan and execute the individual steps of adjustment and thus should have more free cognitive resources for internalizing (i.e. observing and memorizing) the respective processing steps. In the short-circuit condition, the participants could also adjust the infographic, but they could not observe the individual steps of the transformation. Therefore, the participants in the short-circuit condition were not expected to benefit from this type of representation control in the testing phase.

In line with the hypothesis for the practice phase, participants in the active representation control condition showed a longer time on task than the participants in the short-circuit condition (in match and mismatch trials) and also a longer time on task than participants in the modeling condition in match trials. This disadvantage of the active representation control condition might be caused by the additional cognitive resources that were used for planning and executing the relevant steps of the adjustments.

The results for the testing phase were mixed. The results in the match trials were consistent with the hypothesis. The participants of the modeling condition solved the tasks faster than the participants of the untrained baseline condition. No such difference was found between the baseline condition and the both remaining conditions, the active representation control condition and the and short-circuit condition. This result is in accordance with research on the acquisition of problem-solving skills through worked-out examples. Worked-out examples resulted in equal or higher performance than practice with conventional problems (Catrambone & Holyoak, 1989; Paas, 1992). The results in the mismatch trials, however, did not correspond to the hypothesis. The conditions did not differ regarding time on task and proportion correct. That means, none of the three groups with the different forms of representation control could benefit from its previous experience with representation control. When confronted with the tasks without the option to use any form of representation control, they all performed at a comparable level with the untrained baseline condition. To sum up, the results are partly conforming with Salomon´s (1974, 1990, 1994) assumption that modeling epistemic actions may help learners to internalize the individual processing steps as it allows for their observation and memorization. At the same time, the complexity of the transformations seems to have an influence on the effectiveness of the strategy to model such epistemic actions.

General discussion

Visual representations are often used to communicate information. Therefore, in the 21st century, it is an important skill in both the professional and leisure contexts to understand and handle these visual representations (Ananiadou & Claro, 2009). Visual representations can take on a wide variety of formats and often convey various pieces of information at once. This can make it difficult for users to understand visual representations and read off the relevant information. In order to facilitate the handling of visual representations as much as possible, suggestions were developed on how representations can be optimally designed (e.g. Gleicher et al., 2011; MacEachren et al., 2012; Tan & Benbasat, 1993). However, these optimizations depend on the task and the abilities of the user, so that a solution that fits all situations does not exist. One way to deal with this problem might be to give the user representation control, that is the option to adjust the visual representation to the task requirements. As such, representation control consists of one or more interactive functions and serves the user for offloading the otherwise cognitive processing steps onto the external environment, the visual representation. In my dissertation, I have derived two interactive functions from theory and practical advice as an implementation of representation control and investigated their effect on two information extraction tasks.

Summary of research questions, methods, and findings

The three presented studies had the aim to investigate the effect of the availability of representation control on the immediate performance in a goal-free information extraction task as well as its effects on the immediate task performance and on incidental learning in a problem-solving task. I considered the use of representation control (i.e., the adaptation of the representational format to the task requirements) to be a typical example of epistemic actions that are executed in order to offload cognitive processes into the environment. Therefore, in

Study 1, I investigated whether representation control could contribute to a more differentiated and more balanced impression of election results that were depicted in an infographic. In Study 2, I investigated the effect of representation control on problem solving that required the extraction of specific information from the infographic. In Study 3, I extended this investigation of representation control on problem solving by also investigating its influence on incidental learning, that means, how well the information extraction task could be performed when representation control was no longer available.

To test this, I presented the participants of all three studies with infographics that depicted fictitious election results in different spatial organizations. In Study 1, the participants were asked to read off as much information as possible from the infographic. In the other two studies, participants were confronted with questions regarding the depicted information and they were asked to answer these questions. In Study 1 and Study 2, participants could either use or not use representation control during the tasks, whereas in the experiments of Study 3 - that consisted of two phases - the availability of representation control varied between the practice phase and the testing phase. The conditions in which the availability of representation control changed between the two phases, especially when representation control was withdrawn in the testing phase, were of special interest.

Summarizing the results of all three studies, I found a differentiated pattern of the influence of representation control in a goal-free task and a task with a specific goal. In the goal-free task of Study 1, representation control was used, but it did not influence the information that was extracted from the infographics. In contrast, in the task that required answers to specific questions (Study 2), the availability of representation control influenced how fast and accurate the answers were given. Participants with representation control benefitted from this feature. This was especially true when the original spatial organization of the infographic and the task requirements did not match. This result for tasks with a specific goal could be replicated and extended in the three experiments of Study 3. The general benefit of using representation control during task solution also was visible in these experiments.

However, the effects of representation control on task solution when representation control was no longer available (i.e. in the testing phase) limited the positive findings. Participants who had used representation control before fell back to the performance of the untrained baseline condition in those tasks in which the spatial organization of the infographic and the task focus did not match if representation control was spontaneously withdrawn. Compared to participants who never had access to representation control, the previous availability of representation control resulted in lower performance when the spatial organization of the infographic and the task focus did not match in the reproduction task.

Additionally, the group without representation control during both phases failed to transfer its knowledge from the practice phase to the near transfer task in the testing phase. Moreover, participants used the opportunity to reduce information in the visual representation less often in the transfer task of the testing phase when they had practiced without representation control compared to the group that had representation control available in both phases. That suggests that not the availability of representation control during practice is useful for learning the task structure, but - if all - the unavailability of representation control during practice.

In Experiment 3, the more automated types of representation control led to the best performance during the practice phase, but not during the testing phase. The performance during the testing phase was only enhanced when a step-by-step demonstration of the necessary adjustments of the infographic was provided and the spatial organization of the infographic and the task requirements matched.

Implications

Goal-free task vs. task with a specific goal. In all three studies, participants used the option to adjust the infographics to the task demands. However, in Study 1 it did not influence the extracted information. The major difference between Study 1 and the following studies was the character of the tasks. In Study 1, the participants were only instructed to write down as much information from the infographic as possible. In contrast, in Study 2 and Study 3, the task was always formulated as a specific question that should be answered by the participants. From a theoretical perspective, these results suggest that representation control only has an influence on the performance in tasks with a specific goal, but not in goal-free tasks. The main reason behind this assumption is that the tasks with specific goals involve higher cognitive demands which are associated with remembering the goal and planning its achievement. In contrast, in the goal-free tasks, participants can formulate statements based on the presented information without remembering a specific question (Ayres, 1993; Sweller & Levine, 1982). Further planning is only necessary in order to avoid duplicates. As such, a simplification through representation control is only helpful in tasks with a specific goal in which the limits of cognitive processing are exceeded.

From a practical perspective, the two different tasks – the goal-free task of extracting as much information as possible from an infographic as in Study 1 and the specific task of answering given questions as in Study 2 and 3 – resemble two different contexts in everyday life. The goal-free task resembles the reading of a digital newspaper without the intention to answer a specific question in mind. As such, it is a task that most people accomplish in their daily lives. The other task with specific questions resembles more situations in educational contexts such as in schools or universities where students are asked to solve specific problems or answer a given question. Depending on these contexts and tasks, the presented results have different practical implications.

For simple information extraction during reading, the influence of representation control seems to be absent, at least under conditions similar to the ones of Study 1; that is, if two conditions are met: First, if users of interactive infographics have sufficient time to deal with the infographic and second, if the task is to extract as much and as divers information as possible. For other contexts such as the superficial scanning of news, the present studies have limited validity. For the other task, dealing with the infographic in order to find specific information, representation control seems to influence how fast and how correct this information is found. However, a positive influence of representation control in tasks with a specific goal is only present as long as representation control is available but not after it has been spontaneously withdrawn.

Task-performance vs. procedural learning. This limited positive effect of representation control on the immediate task performance without benefitting procedural learning is of special interest both from a theoretical as well as from a practical point of view. From a theoretical point of view, it is interesting because the literature allowed for predicting a positive as well as a negative effect of representation control on subsequent tasks that did not offer representation control. The present results are in accordance with the desirable difficulties approach (Bjork, 1994; Schmidt & Bjork, 1992). This approach states that facilitating the learning process, for instance through offering representation control that allows for cognitive offloading, might result in decreased learning outcomes. For my studies, this implies that representation control can facilitate the extraction of specific information, but it does not promote the general understanding of the structure of the infographic nor the acquisition of strategies to handle infographics without representation control. An additional result of the transfer task is of interest here: Those participants who had practiced without representation control used the opportunity to reduce information less often in the transfer task than the group that had representation control available in both phases. This suggests that not the availability of representation control during practice is useful for learning the task structure, but - if all - the unavailability of representation control during practice. The results of the third study therefore highlight the importance to differentiate between task performance and learning (Soderstrom & Bjork, 2015 for a review).

From a practical point of view, the differentiation between task performance and learning is relevant, as especially in educational contexts, most tasks are not only designed to communicate information to students but also to enable students for the future to master similar tasks by their own. With the results of this dissertation, I could demonstrate that practicing an information extraction task with interactive infographics is only beneficial if in subsequent tasks the infographics also allow the use of these interactive functions. If this was not given, practice did not lead to learning, that means performance in the subsequent tasks was not improved. This distinction between the actual task performance and the sustainable procedural learning should be addressed when training teachers or instructional designers in the design of teaching materials.

Reproduction vs. transfer. In Experiment 2 of Study 3, I further extended the research question and investigated the generalizability of the missing benefit when practicing with representation control to a near transfer task. The main pattern of results was the same for the reproduction and the transfer tasks: The availability of representation control influenced the immediate task performance: if representation control was available, the performance was better. However, some details differed between reproduction and transfer: In the reproduction task, no differences appeared between the conditions in match trials, whereas in the transfer task, the benefit of having representation control available was apparent. Moreover, whereas in the reproduction task, the group that did not have representation control during practice and testing outperformed the group that had representation control during practice but not during testing, no such difference was apparent in the transfer task. As such, the conclusion that practicing with representation control is not useful for subsequent task performance if it is not available in this subsequent task is supported by the results for the reproduction as well as for the transfer task.

From the present results, two additional conclusions regarding the difference between the reproduction and the transfer task are possible: First, the difficulty of the reproduction task in match trials was so low that participants did not benefit from the availability of representation control. In contrast, in the transfer task, the availability of representation control increased performance. This gives an additional hint that the benefit of representation control for task performance is only present if the task is of sufficient difficulty, either due to a mismatch between the task requirement and the organization in the infographic or due to slight variations in the task as a near transfer. Second, whereas participants without representation control in both phases were able to apply their knowledge to the task solution in the reproduction task, they were not able to transfer their knowledge to the task solution in the transfer task. As such, the results show that the differentiation between reproduction and transfer is valid. Even if the difference in the manipulation of both tasks was minimal, it had an effect on the performance of the group that solved all tasks in the mind. It might be, that the mental strategy that was used for solving the tasks is more rigid and does not allow for flexibility. The higher involvement might have led to a better training of the solving strategy and therefore, relearning a new strategy might have been exceptionally difficult. This is one possible explanation why only this group was affected by the different tasks, but further empirical research is necessary to prove that.

Reorganization vs. reduction of information. In the studies with the specific task (Study 2 and Study 3), I consistently found an asymmetry between the use of the two interactive functions: the reorganization was more often used in mismatch trials than in match trials, whereas the reduction of information was consistently used in match and mismatch trials. This pattern of usage suggests that the use of representation control resembles a strategic, purposeful action that is executed with the aim to reduce task complexity and thus to foster task performance. Spoken from a theorist´s perspective, I have succeeded in combining the concept of cognitive offloading with the concept of representation control. Representation control is a much divers concept than the externalizing actions that have been investigated so far with representations (e.g. the rotation and translocation of objects to fit in a given gap or clicking in a presentation window to see a pattern that has to be reproduced; Ballard, Hayhoe, & Pelz, 1995; Gray, Sims, Fu, & Schoelles, 2006; Kirsh & Maglio, 1994; Patrick et al., 2015). Representation control requires that the semantic meaning of the representation is taken into account because the content of the depicted information as well as its format can be adjusted to fit the task requirements. Thus, not only the superficial match of figures is required but the selective presentation of relevant information in a format that is as suitable as possible for the task at hand.

By differentiating between the two representation control functions and using representation control strategically, my participants showed a high level of meta-representational competence. This competence is characterized by the ability to anticipate possible representations, to choose the representation that is the most suitable and to adjust the representation accordingly (Azevedo, 2000; diSessa, 2004; Hegarty et al., 2012). Contrary to the study by Hegarty and colleagues (Hegarty et al., 2012), in which participants should indicate the best-fitting from a given selection, in my studies, the participants could actively adjust the representations according to the task requirements. This might explain why in the present studies the participants adjusted the visual representations to fit with the task requirements whereas in the study by Hegarty and colleagues (Hegarty et al., 2012), the participants tended to select representations that contained irrelevant and thus too much information. However, they were not asked to adjust the representations and the given question was about their preference and not about the suitability of the representation. Thus, it might be a matter of how to ask participants about the most appropriate visual representation. In order to explore the meta-representational competence more in detail, further studies are required that systematically vary the methodology for indicating the most appropriate representation.

Different wordings in the instruction as well as a comparison between selecting from a given range of visual representations opposed to interactively adjusting the visual representation might provide first indications.

In Experiment 2 of Study 3, the usage pattern of the both representation control functions differed between the group that had representation control in both phases and the group that only got representation control in the testing phase. This difference was apparent in mismatch trials of the testing phase but only reached significance for the information reduction function in the mismatch trials of the testing phase. It seems that participants who had to solve the practice phase without representation control also use the mental strategy more often if they have the option to offload the cognitive processing steps that are tied with the mental strategy. This result is in accordance with research that varied the cost of accessing information between trials and investigated whether a memory-based strategy was selected (Patrick et al., 2015). Increased accessing costs led to the use of a more memory-based strategy, even in subsequent trials that did not induce higher access costs.

Cognitive demand vs. unsystematic modeling. In Experiment 3 of Study 3, I tested two possible explanations for the previous finding of Study 3 that the option to use representation control did not benefit the performance in following tasks if these tasks did not offer representation control. The first possible explanation was that the cognitive demands of planning and executing the adjustments to the task requirements during the practice phase were too high and thus the practice phase was not appropriate for preparing for following tasks. The second possible explanation was that the self-executed adjustments were too unsystematic for serving as a model how to solve the tasks and therefore the participants could not benefit from their previous experience of solving the tasks with representation control if this was no longer available in the testing phase.

The benefit of the modeling condition on the time on task in match trials is consistent with the research on problem-solving skills in which worked-out problems resulted in equal or higher performance than practice with conventional problems (Catrambone & Holyoak, 1989; Paas, 1992). However, no benefit of any type of representation control was found for mismatch trials. On the one hand, this pattern of results partly supports Salomon´s (1974, 1990, 1994) assumption about the beneficial effect of modeling epistemic actions on their internalization by the learners. On the other hand, it seems likely that the complexity of solution steps influences how effective this modeling of epistemic actions is. Representation control seems to be effective only if it is highly automated without burdening the planning and execution of the adjustments to the user. Additionally, the adjustments had to be of low complexity and modeled systematically and in a step-by-step procedure allowing the user to follow the transitions. These results show that the explicit modeling of the solution steps of a sufficiently simple task helped the user best to learn the task structure. By defining the limits of the usefulness of modeling to small tasks, I extended Salomon´s (1979) model.

Strengths and limitations

Strengths. The interactive functions that were offered to the participants derived from two theoretical principles of the theory of multimedia learning (Mayer, 2005): The option to reduce information is in accordance with the coherence principle that states that only the relevant information should be presented. The option to reorganize the depicted information is in accordance with the spatial contiguity principle that states that related information should be presented in spatial proximity to each other (Mayer & Fiorella, 2005). Moreover, these two functions were embedded in the concept of representation control, that is the option for the user to adjust a representation to the actual task requirements regarding the representation format and - to a limited degree - regarding the represented content. The conceptual idea of representation control as an instance of epistemic actions that are used to offload cognitive processing to external representations links the research about multimedia learning and information visualization with the research on cognitive offloading and epistemic actions. This theoretical foundation of the offered interactive functions combined with the fact that these functions have also been recommended by renowned practitioners (Bertin, 1967; Tufte, 1983) is a clear advantage of the present work. Nevertheless, it should be investigated in future studies how other interactive functions that allow to control the representation format influence information processing. The literature review demonstrated how divers the concept of interaction is and provides ideas about what other functions could be investigated. In a first study, the individual steps of the task solution process without interactive functions should be analyzed and then, interactive functions should be designed that take over the most demanding or all processing steps. Such a procedure might be helpful, especially for developing sequential modeling functions that are built in order to prepare users for upcoming tasks without interactive functions as it was the case in Experiment 3 of Study 3. It assures that exactly those steps are modeled that the users execute when they are confronted with the task without the option to use interactive functions.

An additional major advantage of this dissertation is that I applied the concepts of cognitive offloading and representation control in empirical research with cartographic infographics. As such, my studies can be seen as a first step from psychology towards an interdisciplinary investigation of interactivity in cartographic materials. A first step from geography has already been done by Roth (2011) in his dissertation in which he promoted the investigation of cartographic interaction. That means, in geography there already exist a few studies that investigated interactivity in maps (e.g. Roth, 2011). However, the focus and methodology of investigation of these studies differ from my reported studies. For instance, Roth (2011) used mainly qualitative methods such as interviews, card sorting or interaction analyses, Harrower and colleagues (Harrower, Keller, & Hocking, 1997) used semantic differentials. In the section about the influence of the data representation on the extracted information, I already mentioned the cognitive map-design research that concentrates on the design of maps with respect to human cognition (Montello, 2002). Its goal is to understand human cognition in order to improve the design and the use of maps. Therefore, it investigates human cognition by using methods and technologies that are also used in psychology or cognitive sciences. Thus, the methodology is closer to the presented studies, but its focus is more on the representation than on interactive functions. Moreover, in the past, the variations of the representations (i.e. the cartographic symbols such as graduated circles) have been minimal so that its relevance suffered from the limitation to low-level perceptual processes without taking into account higher-order cognition (Montello, 2002).

Another approach in geography that is related to the present work does not focus on interactivity but investigates the significance of maps for reasoning processes (MacEachren, 2015). As such, map-based reasoning is understood as an instance of distributed cognition. With this approach, I share the understanding that cognitive processes are not limited to the human mind but can be at least partially externalized into the environment. However, map-based reasoning focusses on data exploration and knowledge construction, whereas in my research, the major aim of interacting with maps was communication and extraction of information. Taken together, there are a few overlaps between psychological and cartographic research. However, regarding the use of interactive functions in cartographic representations (e.g. cartographic infographics or maps) and its consequences on cognition, as far as I know, there is no research yet.

Limitations. Since a dissertation cannot cover an entire field of research, limitations are also imposed on this dissertation. I would ask all readers to consider them carefully before generalizing my results too broadly. At the same time, these limitations also provide indications for future research.

Two limitations concern the population examined. Participants in all studies were mostly students who were familiar with computers and digital devises. Most of them reported to use computers almost daily. This limited diversity in the involved population makes it difficult to generalize my findings to all people. Especially as in the no and low digital media use group, elderly and people with lower educational levels are overrepresented, my findings should be interpreted with caution and require further validations when applied to this population. This limited diversity might also have influenced the results of Study 1 in which I failed to find a difference between the two representation control conditions with and without instruction. As the design of the interactive functionalities was based on common design patterns, users who had experience with interactive digital devices had no problems with using them even without an explicit instruction how to use it. This might have been different, had I recruited a group of participants with less experience in handling digital devices.

Besides the familiarity with digital devices, also other interindividual differences might influence how representation control is used and how it influences task performance and learning. Especially as former studies suggest an influence of ability and metacognitive evaluations on the offloading behavior (Gilbert, 2015; Risko & Dunn, 2015), interindividual differences in the strategies to use representation control and in the underlying meta-cognitive knowledge might be of interest. For instance, the assumptions about one´s own cognitive abilities, such as the short-term memory, might influence how intensively representation control is used. These interindividual differences should be addressed in future research. Risko and Gilbert (2016) proposed a model of the underlying processes on which the empirical research can be based.

Another limitation relates to the instruction of the task. In Study 3, when investigating the effects of representation control on subsequent tasks, the participants were never informed about the withdrawal of representation control in the testing phase. As such, I focused on the investigation of incidental learning. Thus, my results are not automatically generalizable to an explicit learning task. It remains possible that the participants would have learned the task structure had they been explicitly instructed to do so. Thus, further studies should investigate the use of representation control and its effect on task performance and learning in an explicit learning environment. One option for investigating the influence of incidental compared to explicit learning could be to manipulate the instruction that the participants receive. One group could be instructed that, no representation control will be available in a following testing phase, whereas another group receives the same instruction as in the presented studies, that means without the information about the withdrawal. However, for generalization of the results to everyday life, this limitation on incidental learning is less severe as in everyday life most activities include incidental rather than intended learning and thus the studies give a good idea about these situations.

A last limitation to the generalizability of the present results that I want to address relates to the short duration of the experiments, especially of the practice phase. The participants could acquire knowledge about the task structure and the operation of the interactive functions of representation control during the 24 trials of the practice phase. These trials lasted about 45 minutes. It might be possible that a longer exposure to the practice phase would have led to additional knowledge about the underlying task structure. Assuming that the duration was insufficient for learning both, the task structure and the operation of the functions, the operation might have been learned first as it facilitated the actual task performance. Therefore, longer time exposure might have allowed the additional learning of the underlying task structure. This means that representation control may not prevent the learning of the task structure, but only leads to the learning of the operation of representation control first and the learning of the task structure second. In the presented experiments, there might not have been enough time left (in terms of trials) to learn the task structure. This limitation applies more to the theoretical implications than to the practical conclusions because incidental learning in everyday life is also often limited to rather short exposure or only a few trials. In contrast, longer exposure intervals and more repetitions are more commonly used in formal learning environments. Therefore, it makes sense to also investigate these in further studies.

Conclusion

To sum up, representation control offers a solution to the conflict to provide a visual representation that is useful for a wide range of tasks but also that is as simple as possible for the actual task. That means, for one thing, designers can include information in infographics and thematic maps that are relevant to different tasks and thus enhance their usefulness. For another, representation control allows the users to interactively adapt a given visual representation to the requirements of the actual task and thereby increases the ease of use of the visual representation. However, the beneficial effect of representation control was investigated in the present dissertation in detail. I found it to be limited in various regards. First, representation control only facilitated the actual performance when the task required answering a specific question (i.e., when a certain goal was given), but not when goal-free tasks were worked on (e.g. read off as much information as possible). Second, representation control did not benefit the learning of the task structure in preparation of future tasks that did not provide representation control. When participants were confronted with the same or similar tasks without the option to control the representation, their performance dropped.

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DANKE.

Appendix

The manuscripts in the appendix are in the same order of appearance as in the dissertation.

Appendix A

Moritz, J., Meyerhoff, H. S., & Schwan, S. (in preparation). Representation control in a goal-free task: The use of reorganization and reduction in an information extraction task with infographics.

Representation control in a goal-free task: The use of reorganization and reduction in an information extraction task with infographics

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Abstract

Representation control refers to the option to change the format and content of a representation according to the requirements of the task and of the user, that means representation control is a specific form of interaction. Despite the growing use of interactive infographics in newspapers and magazines, little is known about the use of these interactive functions and their influence on the information that is extracted from the infographics. In the present study, participants were asked to read off as much information as possible from an infographic. We coded the statements and analyzed comparisons between two or more information units. The results provide evidence that representation control was used for the task, even when the functions were not explained in detail. For the extracted information, we expected that participants compare more often information units that are located in close proximity to each other than information units that are depicted on different parts of the infographic. However, contrary to this hypothesis, the use of representation control did not influence the number nor the type of comparisons that the participants made. Our results indicate that using representation control might not always be an advantage. We discuss possible reasons for the missing influence of representation control on the extracted information. One of them is the goal-free character of the task that we used in this study.

Introduction

Visualizations are often used in online media to present multifaceted information to users.[1] However, such multifaceted information often can be represented in different ways that suggest different implications. This also includes the perspective[2] from which the data is depicted. As previous research has shown, the perspective from which a topic is approached can influence the information that is taken into account and ultimately influences learning (e.g. Spiro, Coulson, Feltovich, & Anderson, 1988) or the opinion that one builds on a topic (Tversky & Kahneman, 1981). However, at least in journalism, one major aim of communication is to inform users neutrally rather than giving biased views of a topic (Bovée, 1999). According to the data journalism handbook (Gray, Bounegru, & Chambers, 2012), especially interactive visualizations that allow exploration of data provide transparency about the reporting process. That means, including options for interactivity in visualizations is assumed to be of advantage for unbiased information extraction. In the present study, we investigated the effect of interactivity and different spatial organizations of information on the number and type of conclusions that are drawn from a visualization.

One relevant characteristic of visualizations is that not only the information content itself is relevant, but also its spatial position in the visualization is meaningful (Larkin & Simon, 1987, cf. diagrammatic representation). The spatial organization of the information units allows inferences to be drawn about the relationship between them.

Depending on the representation format and the content, users might be encouraged to draw three different types of inferences: Temporal inferences, hierarchical inferences, and relational inferences (McCrudden & Rapp, 2017). The temporal inferences refer to the

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[1] Throughout this manuscript, I use the term “user” rather than “recipient” or “reader” in order to highlight the active participation of the user when interacting with interactive infographics in contrast to mere reception of static displays.

[2] The term „perspective“ is meant in the sense of „ a particular way of considering something” (Cambridge Dictionary).

chronological and sequential ordering of events, for instance a sequence that depicts the genesis of the foehn effect. Hierarchical inferences refer to the structural relation between concepts, including higher and lower level categories. An example of a visualization that allows hierarchical inferences is the organization chart of a company with different levels of organizational units. Relational inferences refer to comparisons between facts or concepts such as the features and function of elements that are used when constructing a building. These three types of inferences are not exclusive; thus, it is possible to draw more than one type of inference from a visualization (McCrudden & Rapp, 2017). The drawing of inferences is thereby influenced by the extraction and localization of information. Extraction relates to the selection of important compared to unimportant information, localization relates to the spatial organization of placing related information close to each other (McCrudden & Rapp, 2017). Both design principles can also be found in the cognitive theory of multimedia learning (CTML; Mayer, 2005). Extraction is in accordance with the coherence principle, localization corresponds to the spatial contiguity principle. This means that it is relevant which information is displayed and in which spatial arrangement it is displayed.

In various domains, empirical research has investigated the influence of representation variation on the inferences that are drawn. For instance, users take task-relevant and task-irrelevant information into account when making inferences from infographics and thematic maps (Canham & Hegarty, 2010). In another study, Hegarty and colleagues (Hegarty, Smallman, & Stull, 2012) investigated the influence of complex compared to simple geographical representations on the performance in an information extraction task. Complex displays – albeit preferred by some participants – do hurt performance regarding the response times and error rates. Another example is that novice users infer higher quality of spatial data with increasing photorealism of the depictions of this data (Zanola, Fabrikant, & Çöltekin, 2009). Further empirical results could also show that novices base their conclusions more on superficial structure of representations than on the underlying principles (e.g. Chi, Glaser, &

Rees, 1981; Novick, Hurley, & Francis, 1999). These results stand in accordance with the assumption that novices possess mostly unconnected fragments of knowledge (”phenomenological primitives”) that they built as superficial interpretations of experiences (diSessa, 1988, 1993). Bennett, Toms, and Woods (1993) investigated the influence of different representation types on information extraction either about high-level constraints (such as the relationships among several variables), or about low-level data (i.e. the values of individual variables). They found differences in adequacy of representation types that suggest that task solutions can be supported by the use of specific representations. A further study dealing with graphs indicated that users infer the type of data from the graphical format in which the data is presented (Zacks & Tversky, 1999). Line graphs are interpreted as trends whereas bar graphs are more often interpreted as discrete comparisons.

From a theoretical perspective, the cognitive flexibility theory (Spiro et al., 1988) highlights the relevance of approaching complex, ill-structured domains from multiple perspectives, for instance through multiple representations. It allows the user to flexibly connect the concepts with various related concepts and thus prevents oversimplification and biases. However, the theory does not explain in detail how these multiple representations should be related or might be designed. These questions are subject of consideration in the taxonomy on the functions of multiple external representations (MERs) by Ainsworth (1999, 2006). This taxonomy helps to understand the benefit of multiple representations. Ainsworth identified three main functions of MERs. MERs can have complementary roles, they constrain the options for interpretation, or they support deeper understanding. They fulfill the first function, the complementation, either through supporting complementary processes or through providing complementary information. The second function, the constraining of interpretation, can be achieved through the use of familiar representations or through inherent structural properties that the different representations have. The third function, the construction of deeper understanding, is achieved by supporting abstraction, extension, or explicitly demonstrating relations between the representations. This taxonomy was developed for representations that are presented simultaneously side by side, but it also can be used to classify representations that learners can assess through interactive learning environments (Ainsworth, 2006). In the present study, only the function to provide complementary information was addressed. The study material depicted election results of two election periods and for two different types of votes in two maps. The structure of information was the same in both maps.

The designer of a visualization can use such associations in order to suggest a certain interpretation. This can be advantageous if the design of the representation helps the user to understand a topic, especially for inexperienced users. However, it can also be a disadvantage or even a threat in the sense of manipulation. The designer of a visualization can intentionally use a representation format that suggests an interpretation of the data in favor of his opinion without indicating that the data might be interpreted differently when represented in another format. In order to overcome this threat, various representations could be presented, and the users could select the representation they consider the most adequate for answering their specific question. Another option is to offer the users the opportunity to adjust the representation interactively in order to relieve them from the spatial reorganization of the information in the mind. With both options, however, users need to know which representation is best for the current situation and select or even interactively adjust them to fit their needs. This competence is known under the term representational competence or meta-representational competence (diSessa, 2004; diSessa & Sherin, 2000; Kozma & Russell, 1997; Novick et al., 1999). As the empirical results are mixed it is still unknown whether or under which conditions users have this competence. On the one hand, previous research has shown that users sometimes prefer unnecessarily complex representations suggesting that they do not have the competence of selecting the most appropriate representation (Hegarty et al., 2012; Vessey & Galletta, 1991). On the other hand, it was shown that college students are able to assess how suitable different forms of diagrams are for a given problem solving task (Novick et al., 1999). Moreover, regarding the use of interactive functions, it was shown that users make appropriate use of such interactive functions when learning with videos (e.g. stopping or browsing), resulting in higher performance (Merkt, Weigand, Heier, & Schwan, 2011; Schwan & Riempp, 2004).

Interaction: Representation control - Epistemic actions - Cognitive offloading

As I already mentioned in the previous section, one option to offer divers perspectives on a topic is to allow the user to interactively change the representations, for instance their content and their format. Providing the user with the option to change the representation resembles the concept of learner control in e-learning environments (Kalyuga, 2007; Scheiter, 2014; Scheiter & Gerjets, 2007). Learner control allows the learner to control the pacing and sequencing of information, to control the representational formats (e.g. modality) in which the information is given and to control the content (e.g. amount of information).

One of the aspects of learner control is representation control that allows the user to select the form in which the information is presented (Scheiter & Gerjets, 2007). However, in my understanding, representation control also allows the user to vary the content that is depicted by selecting from a predefined set of variables. Thus, I define representation control as is the option to change the form of presentation of the displayed information in order to adjust it to the task requirements. In the present study, representation control gives the user the option to select the information and to spatially reorganize it in the external representation. Representation control consequently allows the user to offload otherwise covert processing steps from working memory by turning them into overt actions on the external representation. As such, these overt physical actions serve a cognitive function and correspond to the definition of epistemic actions (Kirsh & Maglio, 1994; Parsons & Sedig, 2011). These epistemic actions replace the cognitive processing steps and thus externalize the processing from the mind to the environment. This externalization is the key process of cognitive offloading, that is “the use of physical action to alter the information processing requirements of a task as to reduce cognitive demand“ (Risko & Gilbert, 2016). It allows to overcome the internal limitations of information processing and memory capacity (Baddeley, 1986; Clark, 2008; Miller, 1956; Risko & Gilbert, 2016).

Information graphics

One specific type of visualizations that is used in the present study are information graphics (or in short infographics). Infographics consist of text, images and graphical means, that are combined to communicate information, data or knowledge effectively (Holsanova, Holmberg, & Holmqvist, 2009; Weber & Wenzel, 2013). Those single elements can be attached to each other or embedded one into another, together forming the infographic. As in other visualizations, too, not only the information content but also its spatial position in the infographic is meaningful (Larkin & Simon, 1987, cf. diagrammatic representation). Thus, the spatial organization may suggest specific comparisons between information entities that are depicted close to each other. In contrast, other comparisons between information entities that are depicted in different parts of the infographic, for instance in two different diagrams or maps, might be less obvious and therefore less often drawn.

The present study focuses on cartographic infographics: Election results for different districts were depicted in two thematic maps. The maps contained information on different election periods and on two different types of vote. Comparisons between the different information units were suggested by the proximity of information units and thus by the spatial organization of the infographic.

Research Questions and Hypotheses

The purpose of this study was to investigate the effect of representation control and different information organizations on the conclusions that are drawn from these information graphics. More specifically, we tested how the availability of representation control during an information extraction task affects the number, type and sequence of these conclusions. We implemented a representation control condition in which participants had the opportunity to interactively reorganize a given infographic and select the information that is depicted. The participants were asked to formulate statements about the depicted data. In the analysis, we focused on comparisons between data points as the representation of data in the infographic suggested comparisons. The participants' statements were compared to both a condition in which representation control was available but not extensively introduced to the participants in the instruction section (representation control without instruction) and to a condition in which participants solved the task without representation control (no representation control condition).

Based on the stated theoretical background, we had three hypotheses regarding the information extraction with interactive infographics. Firstly, we hypothesized that the groups that had representation control available during the information extraction task use these interactive options in a strategically expedient way in order to facilitate the task. That means, we assumed that they change the spatial organization at least once in order to see the data in a different spatial context and therefore be able to read off more comparisons from the infographic. Regarding the difference between the two conditions with representation control two results could be anticipated. On the one hand, the participants without instruction had to test how the representation control functions can be operated and thus used it more often than the group with instructions. On the other hand, there might be some participants who do not understand how to use the functions and thus use them less often or never, resulting in lower usage. Secondly, we expected that the invested mental effort for extracting information is lower when using representation control. Therefore, users of the groups that had representation control available were expected to extract more information from the infographic and thus, generate more statements than the group without representation control. Thirdly, as the groups with representation control could change the spatial organization, the difficulty of extraction of comparing information should be comparable for both types of spatial organizations. Therefore, we hypothesized that the groups with representation control generate a comparable amount of comparisons that are prompted by both spatial organizations, whereas the group without representation control was expected to produce more comparisons that reflect the original spatial organization of the infographic.

Methods

Participants

The sample consisted of 121 participants who were recruited from the participant pool of the Leibniz-Institut für Wissensmedien, Tübingen. Two participants had been excluded due to technical failure. Two more participants had been excluded due to non-compliant behavior. One of them extracted only one statement from the infographic, but pressed 1110 times the confirmation button. The other person submitted 243 statements of which 240 were empty. The final sample thus consisted of 117 participants (M = 23.62 years, range 19-30 years, 92 females, no reported color impairments). The experimental procedure has been approved by the ethics committee of the Leibniz-Institut für Wissensmedien, Tübingen. All participants gave written informed consent prior to testing.

Apparatus

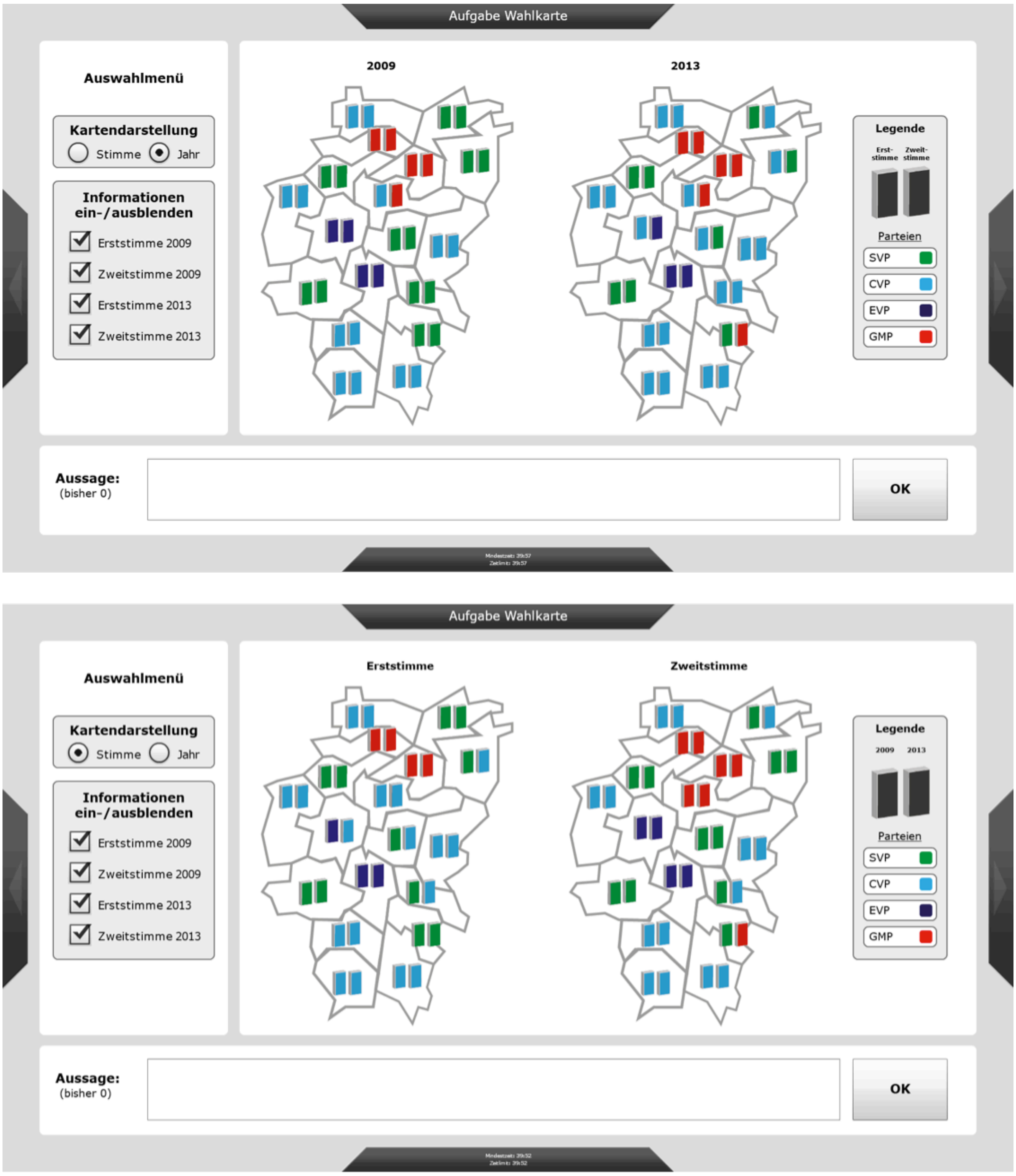
The experiment was conducted on Microsoft Surface Pro2 tablets with a 10.6-inch screen (1920 x 1080 pixels). Responses were recorded using Microsoft Surface Type Cover 2 and an Apple A1152 Wired USB Mighty Mouse.

Materials and Procedure

The information graphics consisted of two maps that were arranged side-by-side. Both maps depicted the same fictitious country consisting of 18 districts. The maps showed the results of two elections for two types of votes. Within each district, two colored bars indicated the winner's party (see Fig. 1). The two types of votes were called first and second vote (inspired by the German election system).

For half of the participants (counterbalanced within condition), the infographic was initially organized by election period (i.e. the 2009 election on the left side and the 2013 election on the right side). For the remaining half of the participants, the infographic was initially organized by the type of votes (i.e. the first votes on the left side and the second votes on the right side). Participants were randomly assigned to one of the three experimental conditions. According to their condition, they received different instructions and interactive features.

At the beginning of the experiment, the participants received instructions regarding the infographic, as well as the task. This instruction encompassed six slides. On the first slide, the participants were welcomed. The second slide provided information about the topic of the infographic as well as general information about the representation. On the third and fourth slide, the two different spatial organizations were explained and demonstrated in an example. The fifth slide declared the task. The last slide announced the beginning of the task. Additionally, the participants in the representation control condition with instruction received an instruction regarding the operation of the interactive features. This instruction was presented between the fourth and the fifth slide. Participants in the representation control condition without instruction received exactly the same introduction but without the slide that explained the operation of the interactive features. However, they were also told that the infographic was interactive, always writing about "the interactive infographic". The no



Kartendarstellung ○ Stimme ● Jahr

☑ Erststimme 2009
☑ Zweitstimme 2009
☑ Erststimme 2013
☑ Zweitstimme 2013

Kartendarstellung ● Stimme ○ Jahr

☑ Erststimme 2009
☑ Zweitstimme 2009
☑ Erststimme 2013
☑ Zweitstimme 2013

Fig 1. Illustration of the information graphics used. For half of the participants, the maps were initially organized by type of vote (a). For the remaining half, the initial layout of the maps was organized by election period (b). Interactive reorganizations were not possible in the static condition. In this condition, the interaction menu (left) was presented inactive and grayed out.

representation control condition received basically the same instruction as the representation control condition without instruction; however, the adjective “interactive” qualifying the infographic had been deleted.

The participants were asked to extract information from the depicted infographic and type it in a blank text box: “Your **task** is to read out information from the (interactive) infographic and to write it in the text box. After each statement, please press the OK button. The **goal** is to generate as many correct statements as possible. For that, you have **40 minutes**.“

After typing a statement, the text box appeared once again blank and a new statement could be typed in. Additionally, in order to visualize that the former statement had been recorded, a counter showed the number of recorded statements. This phase lasted 40 minutes. The participants were asked to generate as much correct statements as possible. During this time, participants in the two conditions with representation control could reorganize the infographic (i.e. altering between the two organization criteria of the maps) or reduce information density (i.e. eliminating information) with the corresponding menu on the left side of the screen (see Fig. 1). This menu was greyed out and inactive in the no representation control condition.

Coding and Analysis

All statements were coded by two coders. They decided whether a statement consisted of a comparison of two or more information entities, a simple fact, meaningless information, or the duplicate of a previous statement by the same person. Regarding the comparison of two or more information entities, the coders had to decide which type of comparison the statement included. Three types of comparisons were considered. 1) A comparison between the two types of votes for a given election period, 2) a comparison between the two election periods for a given type of vote, or 3) a comparison between two or more parties within one election period and type of vote. For instance, the statement ‘In seven election districts did party SVP gain the majority of first and second votes in 2009.’ focused on a comparison between the types of vote for one election period whereas the statement ‘In four election districts did the party SVP gain the majority of first votes, in both 2009 and 2013.’ focused on a comparison of the first votes between the two election periods. The statement ‘Party CVP gained the majority in first votes in 2013 in six election districts more than party SVP did.’ focused on a comparison between parties for one type of vote during one election period.

An example for a simple fact statement is “In 2009, the party GVP gained the majority of first votes in two election districts”. This statement contains information about one party and one type of vote during one election and therefore does not contain comparisons. The category meaningless information encompasses on the one hand sentences like “In 2009, more votes for SVP.” that contained unspecific information that could not be judged as correct or incorrect. On the other hand, the category meaningless information encompasses sentences that correspond more with an interpretation than a factual statement that derives from the extracted information, for instance “In 2009, even when forming a coalition between a large and a small party, no government majority can be formed (regarding the first votes).“ Sentences were coded as duplicates of a statement, when the same person has stated exactly the same information before. For example, a participant writes “In 2013, the party CVP is the winner regarding the second votes.” as statement number five, and as statement number 31, she writes “In 2013, the CVP is the most powerful party regarding the second votes”. Then, the latter statement is coded as duplicate and hereafter excluded.

The inter-rater reliability of the codings was calculated using Krippendorff ́s alpha. For statements containing comparisons of the types of vote it was α = 0.68 (agreement: 88.6 %), for comparisons of the election periods it was α = 0.86 (agreement: 94.1 %), and for comparisons of the parties it was α = 0.65 (agreement: 85.1 %). Statements for which the two codings did not coincide were additionally coded by an independent third coder. Statements that were coded by two coders as simple facts, meaningless information or duplicates were excluded from further analysis (28.86%).

The number of reorganizations was defined as the number of clicks on the interaction menu that resulted in a change of the spatial organization criterion. The number of actions in order to reduce information was defined as the number of clicks that served for changing the visibility of information in the infographic. Importantly, as the information was distributed among four different units (first votes in 2009, second votes in 2009, first votes in 2013 and second votes in 2013), participants had to click twice for reducing the depicted information to the relevant level. Thus, the numerical values for coding the reduction behavior were higher than for the reorganization behavior.

Match and mismatch statements.

The combination of the two map organizations and the three types of comparisons that the statements could contain resulted in match and mismatch comparisons: In match comparisons, the participant compared information that was originally depicted in one of the maps whereas in mismatch comparisons the participant compared information that was originally depicted among the two maps. Importantly, the terms match and mismatch refer to the initial organization of the infographic prior to any self-initiated changes in the spatial organization of the maps. Moreover, the categorization into match and mismatch comparisons is not exclusive, that means, some statements contained a comparison of information that was depicted in one map and an additional comparison of information that was depicted spread over both maps. Therefore, we report an analysis including the coding for match comparisons and an analysis including the coding for mismatch comparisons. On a conceptual level, comparisons that are coded as a mismatch indicate a change of perspective, either through a mental integration of information or through the possible change in the spatial organization of the depicted information in the representation control conditions. In these cases, participants did not rely on the given organization but put the information in another organization form and thereby constructed a new context for it.

Results

Use of interactive functions

Reorganization.

In order to analyze whether participants in the two conditions with representation control used the option to change the spatial organization of the infographics differently, we conducted a *t*-test on the number of changes to the organization of the infographic. The *t*-test revealed that the number of reorganizations did not differ between the condition with representation control with instruction and the condition with representation control without instruction, $t(77) = 0.49$, $p = .624$, both conditions using the reorganization function on average ten to eleven times (with instruction: $M = 10.93$, $SD = 7.51$, without instruction: $M = 10.10$, $SD = 7.32$).

Reduction of information density.

In analogy to the analysis of reorganizations, we also analyzed the reductions of information density in a *t*-test. We observed a similar pattern of results: The number of reductions did not differ significantly between the condition with representation control with instruction and the condition with representation control without instruction, $t(74.15) = 1.23$, $p = .221$. Participants in the condition with instruction changed the visibility of information on average M = 44.56 times (SD = 38.33), participants in the condition without instruction changed the visibility of information on average M = 35.03 times (SD = 30.61).

Number of statements

In order to analyze whether the number of comparison statements differed in the three conditions, we conducted an analysis of variance (ANOVA) on the number of comparison statements. There was no evidence for differences in the number of comparison statements that the participants produced in the three conditions, $F(2,114) = 0.70$, $p = .498$. The participants in the static condition produced $M = 24.29$ ($SD = 10.52$) comparison statements, the participants in the condition with representation control with instruction produced $M = 24.43$($SD = 9.33$) comparison statements and the participants in the condition with representation control without instruction produced $M = 26.97$ ($SD = 13.57$) comparison statements.

Proportion of match and mismatch statements.

In order to analyze whether the conditions influenced how often a match or a mismatch statement was produced, we calculated a generalized linear model with random intercepts for participants. As the statements were coded as match/no match and as mismatch/ no mismatch comparison, the dependent variable was binomially distributed and treated as such.

Match statements. Regarding the probability that a comparison was coded as including information from only one map (match) or not including information from only one map (no match), we did not find a difference for the conditions, $\chi^2(2) = 1.10$, $p = .576$. However, the significant intercept of the model ($\chi^2(1) = 16.97$, $p < .001$) indicated that the probability for comparisons that were coded as matching was higher than the probability for comparisons that were not coded as matching. The mean number of match statements was $M = 16.28$, $SD = 9.17$, the mean number of statements that were not coded as matching was $M = 8.95$, $SD = 8.53$.

Mismatch statements. The same analysis as for match statements was conducted for mismatch statements. Regarding the probability that a comparison was coded as including information from both maps (mismatch) or not including information from both maps (no mismatch), we also did not find a difference for the conditions, $\chi^2(2) = 3.97$, $p = .138$. In this case, also the intercept did not reach significance, $\chi^2(1) = 2.25$, $p = .134$, indicating that the probability for comparisons that were coded as mismatching was comparable with the probability for comparisons that were not coded as mismatching. The mean number of mismatch statements was $M = 12.21$, $SD = 9.48$, the mean number of statements that were not coded as mismatching was $M = 13.02$, $SD = 9.56$.

Discussion

The present study investigated whether people use interactive functions when exploring information graphics. In the present study, the participants were asked to explore the infographic and extract information from it. In line with our hypothesis, the groups with representation control used these interactive options. However, both groups with representation control used it on a comparable level irrespective of whether they were provided with the instruction how to handle the control tools or not. Moreover, the study investigated the influence of the option to use representation control on the number and type of information that was extracted from the infographic. Contrary to our expectations, there were no differences in the number or type of statements that were produced by the three groups. Participants in all three groups produced on average between 24 and 27 statements. The proportion of comparisons that contained information from both maps to comparisons that contained information only from one map was constant across the three groups.

In accordance with prior results on the use of interactive functions in learning with videos (Merkt et al., 2011; Schwan & Riempp, 2004) the study demonstrates that people use interactive functions when exploring information graphics. These results are also consistent with research on the utilization and acceptance of interactive infographics in real online newspapers (Zwinger, Langer, & Zeiller, 2017; Zwinger & Zeiller, 2017). In an online survey with readers of online newspapers, 85% of the participants responded that they used the option to interactively manipulate infographics at least moderately intensive, whereby only 31% reported intensive or very intensive use of infographics. In contrast to the present study that used fictitious infographics, Zwinger and Zeiller (2017) asked readers of online newspapers about their experience with real infographics.

While in Zwinger & Zeiller (2017) only 36 % of the respondents rated the recognizability of the control tools as “very well” or “good”, this aspect has not been a problem in the present study. Participants with and without instruction used the interactive features on a comparable level. This might be due to the long time that participants were asked to spend with the task. The participants had 40 minutes time for exploring the infographic and its interactive functions, and for extracting information from the graphic. They might have used the time for exploring the infographic and its interactive features through trial and error. There were mainly two different interactive functions: restructuring the information that is depicted in the infographic and reducing the depicted information. Both functions were rather basic and could be operated from an interaction menu. People, who use digital devices on a regular basis, should be familiar with the operation of such basic interactive functionalities as an interaction menu. As our participants reported daily use of a computer in the demographic questionnaire, we assume that the operation of the interaction menu was self-explaining to them or at least graspable after executing it once, so no differences in the use of the interactive features between the two groups was found. From this aspect of the present experiment emerge two suggestions for future research. First, the use of representation control with and without explicit instruction should be investigated with people, who do not daily use computers. Their experience with and knowledge about interactive functions might be limited, resulting in a higher need for instructions. Thus, the group that does not receive instructions about the interactive functions might use the functions less.

Additionally, in real world contexts, users rarely spend 40 minutes on an infographic in order to extract all information out of it considering all possible comparisons of the data. The extensive time in combination with the instruction could have led the participants to produce as many and as diverse statements as possible, including all possible comparisons. Consequently, in further studies, the time on task that participants can use for exploring the infographic and testing all functions should be restricted to shorter intervals. This limits the options to apply a trial and error strategy. Additionally, it would also be more realistic in terms of the use of online newspapers in everyday life as readers normally do not spend more than a few minutes on an infographic.

Regarding the more important research question whether the option to use representation control influences the amount and type of information that is extracted from the infographic, the results did not support our hypothesis. There were no differences between the groups regarding the number of comparison statements and regarding the type of comparisons that were made. In all three groups, more comparisons were expressed that contained information depicted on a single map than comparisons of information that was depicted spread over the two maps. It seems that the use of representation control did not influence the information that was extracted from the infographic.

One reason for this result could be the content of the infographic. It depicted voting results in a fictitious country. This assured that no prior knowledge or attitude towards the content existed, but also led the experiments away from real scenarios. Readers of newspapers rarely read information graphics without an attitude towards the topic. So, for future research, the interaction between attitude and attitude-confirming representations on the usage of interactive features and the information that is extracted from the infographics should be investigated.

Another reason for the result that representation control did not influence the information that was extracted from the infographic could be the task. The participants were asked to extract information from the infographic, a relatively unspecific task without a defined goal. As such, it resembles a goal-free problem (Ayres, 1993; Sweller & Levine, 1982). Ayres (1993) and Sweller and Levine (1982) investigated how such an unspecific instruction (e.g. “find all unknown angles”) compared to a specific instruction (e.g. “find X”, the goal angle was marked with an X) influenced the learners´ performance. They could show that learners with the unspecific instruction solved more problems successfully. This disadvantage of instructing a conventional specific goal is explained by the increased cognitive load during the intermediate processing steps that emerges in backward-working heuristics such as the means-ends analysis. The means-ends analysis is a problem-solving strategy that aims at reducing the difference between the actual state and the goal state (Newell & Simon, 1961, 1972). As in the present study the cognitive load was reduced due to the goal-free character of the task, the influence of the option to offload cognitive processing steps onto the environment might be less pronounced. Cognitive offloading, defined as „the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand“ (Risko & Gilbert, 2016, p. 676), has previously been investigated mainly in tasks with specific goals (e.g. Gilbert, 2015; Patrick et al., 2015; Risko & Dunn, 2015; Risko, Medimorec, Chisholm, & Kingstone, 2014). Thus, the goal-free character of the task might have caused that no differences between the three groups occurred when reading infographics. However, the option to adjust the infographic and thus offload cognitive processing onto the environment might influence performance in a conventional task with a specific goal, such as answering a question regarding specific information. Therefore, in following studies it should be investigated how the option to offload cognitive processing influences performance when the participants are confronted with a task that requires answering a specific question.

To sum up, in accordance with our hypotheses, the participants used representation control when extracting information from complex infographics. However, the availability of representation control had no influence on the number and type of inferences drawn, leading to a comparable number of statements for the groups with and without representation control.

One assumption is that the lack of advantage of representation control was related to the goal-free character of the task. This assumption has yet to be substantiated in subsequent studies.

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Appendix B

Moritz, J., Meyerhoff, H. S., Meyer-Dernbecher, C., & Schwan, S. (2018). Representation control increases task efficiency in complex graphical representations. *PLoS ONE*, *13*(4), 1–14. https://doi.org/10.1371/journal.pone.0196420

RESEARCH ARTICLE

Representation control increases task efficiency in complex graphical representations

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Abstract

In complex graphical representations, the relevant information for a specific task is often distributed across multiple spatial locations. In such situations, understanding the representation requires internal transformation processes in order to extract the relevant information. However, digital technology enables observers to alter the spatial arrangement of depicted information and therefore to offload the transformation processes. The objective of this study was to investigate the use of such a representation control (i.e. the users' option to decide how information should be displayed) in order to accomplish an information extraction task in terms of solution time and accuracy. In the representation control condition, the participants were allowed to reorganize the graphical representation and reduce information density. In the control condition, no interactive features were offered. We observed that participants in the representation control condition solved tasks that required reorganization of the maps faster and more accurate than participants without representation control. The present findings demonstrate how processes of cognitive offloading, spatial contiguity, and information coherence interact in knowledge media intended for broad and diverse groups of recipients.

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Introduction

Complex graphical representations such as depictions of the results of elections frequently occur in traditional as well as online media [1,2]. While complex graphical representations appear in many different forms, they all share a spatial organization of visual/pictorial and verbal information. However, as goals and information needs vary between different observers, complex graphical representations typically include unnecessary information that needs to be ignored. For instance, consider a graphical representation depicting the development of state elections across two election periods. When one observer is interested only in the outcome of the current elections, he or she needs to ignore all information related to previous elections, whereas a second observer who is interested in the change between the last and the present election needs to attend to the full information. In the present study, we investigated whether representation control (i.e. the ability to alter the representation of the displayed information)

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enhances the efficiency as well as the accuracy of extracting relevant information from complex graphical representations.

For printed media, designers of graphical representations face a conflict between ease of use and usefulness: When the viewers' information task is known in advance, the graphical representation can be tailored accordingly by leaving out task-irrelevant information and focusing on task-relevant information [3,4]. The graphical representation may then be kept simple, maximizing ease of use, but on the other hand, the usefulness of the graphical representation is restricted to only one specific task. Alternatively, designers may choose to include more information in the graphical representation than is necessary for one particular task. In this case, the graphical representation is suitable for a broader range of tasks/questions. Consequently, the usefulness of the graphical representation is maximized, but information may be cluttered, impeding the extraction of the information relevant for a specific task. In return, this restricts the ease of use.

Digital graphical representations (e.g., in online media) offer a solution to mediate this conflict between ease of use and usefulness; designers may include information suitable for a wide range of tasks and allow the viewers themselves to interactively adapt a given graphical representation to their individual needs and task requirements. While such interactive graphical representations seem to combine both a high degree of ease of use and usefulness, adapting graphical representations requires metacognitive knowledge as well as task-specific knowledge about the structure of the current task. Furthermore, a new tradeoff arises between the motoric and cognitive costs of altering the depicted information and the reduced cognitive effort that is necessary to subsequently comprehend the altered information (see also [5]).

Tradeoffs between costs of motoric actions and cognitive effort are not unique for graphical representations but provide a rather broad principle of cognitive psychology. In fact, even actions such as writing notes or calendar entries can be considered to be cognitive offloading in order to relieve internal processing capacities. This externalization of internal processes is referred to as cognitive offloading [6,7] that is defined as "the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand" [8]. Scaife & Rogers [9] identified computational offloading as one of three central characteristics of using external representations for problem solving (besides re-representation and graphical constraining). They also assume that the use of graphical representations reduces cognitive effort in problem solving. In a similar vein, in information visualization research, three purposes of physical actions on data visualizations were identified: external anchoring for coupling of internal and external representations, information foraging, and cognitive offloading of memory [10]. Remarkably, the externalization processes of cognitive offloading are not restricted to memory representations, but also include physical transformations that aim at avoiding corresponding mental operations [11]. For instance, Kirsh and Maglio [12] demonstrated that participants rather perform motoric actions that alter the representation of information in the environment (i.e. rotating Tetris blocks) than simulating the outcome of the motoric action mentally (i.e. corresponding mental rotation). However, it is unclear whether in complex graphical representations such externalizations of transformation processes are executed, as the representations involve semantic meaning and combine multiple representation formats. The transformation of complex information requires more knowledge about the exact type and organization of the required information, about the task structure, and about the strategy how to achieve an optimal information representation. Thus, requirements—such as metacognitive knowledge—for cognitive offloading in interactive graphical representations are higher than in the above-mentioned studies. In the present study, we tested whether the principles of cognitive offloading also apply to the usage of interactive features in these complex graphical representations.

With regard to information complexity, infographics clearly exceed the materials of previous studies on cognitive offloading. These studies used Tetris blocks [12] or colored squares in the pattern copy task for investigating the cognitive offloading of mental rotation or memory [7,13,14]. Others used rotated text displays [15], sets of letters [16,17] or simple geometrical figures [17,18]. Successful offloading of cognitive processes on infographics requires an adequate adaptation of the depicted information to the task at hand. Representation control allows the user to adapt the representational format to the task requirements [19,20]. With regard to cognitive offloading, representation control allows for the externalization of the spatial transformation as well as the selection of depicted information. In our study, these two fundamental transformations were enabled as part of representation control: (a) changing the spatial logic of the graphical representation, that is, the meaning of distances between different elements (i.e. spatial organization), and (b) reducing information density according to the relevance of information (i.e. selection). As the selection does not influence the spatial layout of the infographic, a reduction of information results in lower information density. These transformations were selected because they are based on well-studied principles of cognitive processing of multimedia [21–24] as well as practical advice [3,25].

The change of spatial organization affects the spatial contiguity (i.e. spatial proximity) of the depicted information [21–24,26]. Studies on learning from text and pictures showed enhanced learning performance when text and picture are integrated rather than presented separately [27]. An explanation for this effect is that search and integration of corresponding pieces of information require additional cognitive processing. These resources then are missing for elaboration and knowledge transfer [28], resulting in lower performance in des-integrated formats. Studies that have investigated the cognitive processes in multimedia learning through eye tracking have additionally demonstrated that participants make fewer eye movements connecting the corresponding information units in split formats or even ignored information units [29,30]. An advantage of integrated presentation formats is found not only in learning tasks but also in visual comparison tasks. Higher working memory use in trials with larger distances explains this effect [31,32]. However, optimal spatial organizations vary between different tasks. In other words, different tasks may require different information elements to be presented close to each other. Therefore, while the fixed layout of a graphical representation may foster solving a particular task, it may be detrimental for a range of different tasks. As a possible solution, providing representation control comes into play in order to allow for switching between different spatial organizations of the graphical representation.

The second transformation (selection) is based on the distinction between relevant and irrelevant information. According to the coherence principle of the cognitive theory of multimedia learning [22], simpler displays are more beneficial for learning. Two solutions for indicating this distinction between relevant and irrelevant information were proposed: the highlighting of relevant information and the removal of irrelevant information [33]. Studies on weather maps underpin the effectiveness of these two solutions. Regarding highlighting, studies have shown an influence of information salience on information processing [34–36]. Similarly, experimental conditions with task-irrelevant information impaired performance relative to conditions without irrelevant information [37]. Furthermore, irrelevant information included in maps led to longer processing time and less accurate responses [4]. Remarkably, this advantage of the reduction to relevant information stands in contrast to preferences for realistic and thus complex displays. Map users tend to choose more realistic and complex maps over abstract and reduced ones [4,38,39].

In the present study, we investigated how representation control contributes to cognitive offloading as well as task performance, using complex graphical representations as stimuli. We asked participants to perform an information extraction task with political maps on which the relevant information was either spatially aligned (match) or misaligned (mismatch) with the task demands. In our experiment, we compared offloading as well as performance between two groups that were either allowed to alter the graphical representation (i.e. representation control) or not (static condition). We hypothesized that when available, representation control will be used in a task-appropriate manner to increase task effectiveness. More specifically, we predicted:

(a) Users provided with representation control will adjust the complex graphical representations in cases in which the overall spatial organization does not correspond to the task requirements.

(b) Users with representation control will reduce the information density of the complex graphical representations in order to increase coherence of the depicted information.

(c) Users with representation control will be faster in the information extraction tasks with (initially) mismatching graphical representations than users in the static condition.

(d) Users with representation control will be more accurate than users in the static condition.

Methods

Participants

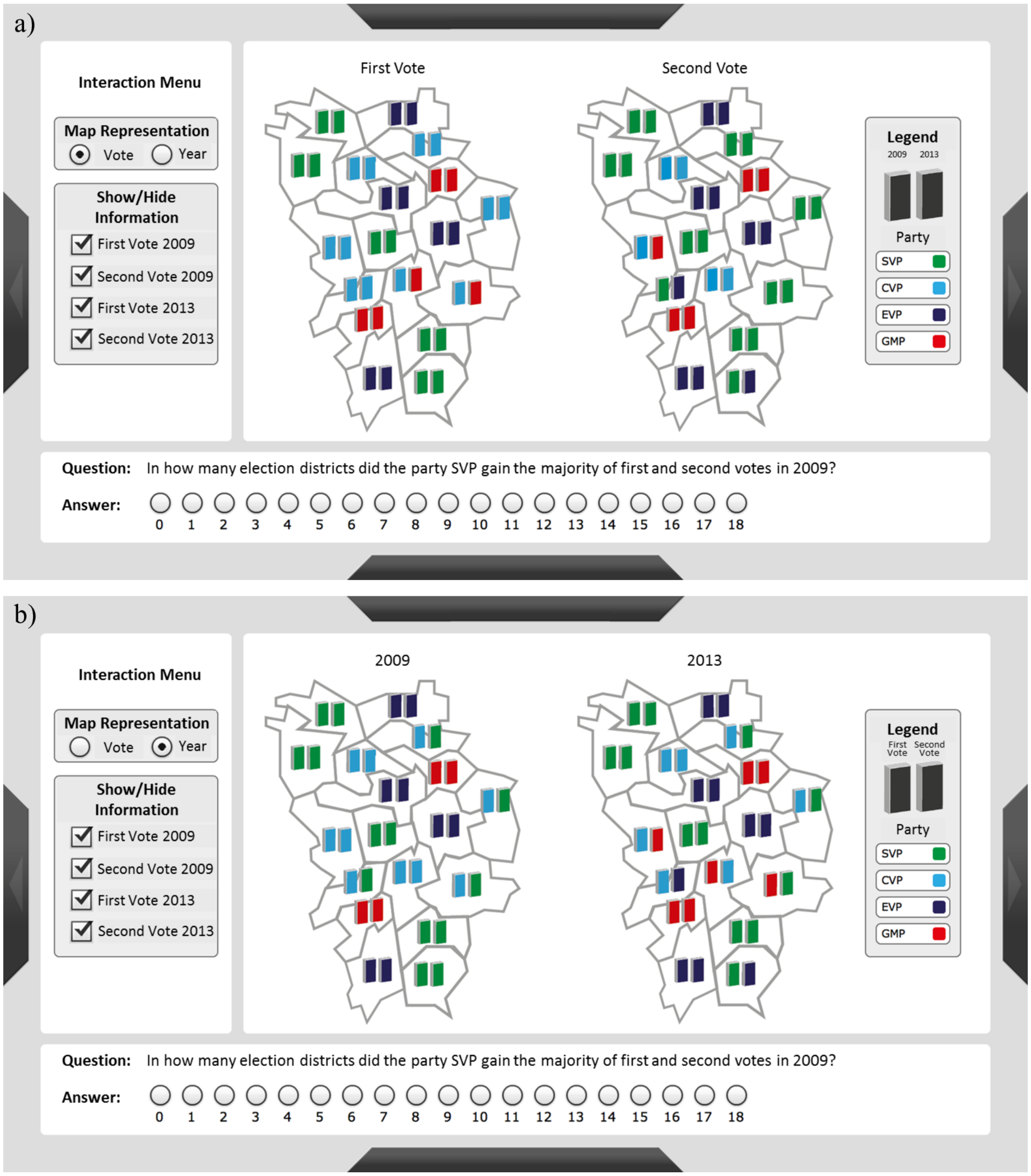
The final sample consisted of 88 participants (66 female; mean age: 27.5 years, range 19–63 years) who were recruited from the participant pool of the *Leibniz-Institut für Wissensmedien*, Tübingen. They were randomly assigned to the two experimental conditions. The experimental procedure was approved by the ethics committee of the *Leibniz-Institut für Wissensmedien*, Tübingen. Most of the participants were university students (90%) with a relatively high self-reported experience in the use of computers (on a scale from 1 (daily use)—to 4 (practically no use): $M = 1.06$; $SD = 0.27$) but low self-reported experience in the use of tablets ($M = 3.48$; $SD = 0.94$). All participants provided written informed consent prior to testing. They received monetary compensation (10 €). One participant was excluded due to self-reported color blindness. An additional participant was excluded due to no correct responses (and therefore no valid data for RT analyses) in the mismatch trials. Both participants were part of the static group.

Materials

Hardware. The experiment was conducted on Microsoft Surface Pro2 tablets with a 10.6-inch screen (1920 x 1080 pixels). All user input was given through the touch-sensitive display.

Graphical representations. The graphical representations included two maps that were arranged side by side and depicted fictitious election results of two consecutive election periods and two types of votes. The two types of votes, called first vote and second vote, were based on the German election system, in which the seats of the parliament are distributed according to the combined result of the two types of votes. The exact layout and the components of the display are depicted in Fig 1. Each map consisted of 18 districts with two colored bars. The bars showed the color of the winner´s party and were explained in a legend.

The depicted election results were either organized by type of vote (Fig 1A) or election period (Fig 1B). In the organization by election period, the left map showed the election results for the first election period, while the right map showed the results for the second election period. The left bars in each map represented the first votes, whereas the right bars represented



a)

Interaction Menu

Map Representation
● Vote ○ Year

Show/Hide Information
☑ First Vote 2009
☑ Second Vote 2009
☑ First Vote 2013
☑ Second Vote 2013

Question: In how many election districts did the party SVP gain the majority of first and second votes in 2009?

Answer: ○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18

b)

Interaction Menu

Map Representation
○ Vote ● Year

Show/Hide Information
☑ First Vote 2009
☑ Second Vote 2009
☑ First Vote 2013
☑ Second Vote 2013

Question: In how many election districts did the party SVP gain the majority of first and second votes in 2009?

Answer: ○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10 ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18

Fig 1. Layout and components of the graphical representation for the representation control condition. The pair of maps in the center of the screen is surrounded by the interaction menu on the left and the legend on the right. The question/answer field is located below the maps. a) The graphical representation is organized by type of vote, resulting in a mismatch trial when combined with the depicted question. b) The graphical representation is organized by election period, resulting in a match trial when combined with the depicted question.

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the second votes. In the organization by type of vote, the left map showed the results for the first vote, and the right map showed the results for the second vote. Further, the left bar showed the winner of the vote in the first election period, and the right bar showed the winner of the second election period.

The questions in the question/answer field either focused on the two types of votes within one election period or on one type of vote across the two election periods. For instance, the question ‘In how many election districts did the party SVP gain the majority of the first votes, in both 2009 and 2013?’ required the participants to compare the first votes of the two election periods, whereas the question ‘In how many election districts did the party SVP gain the majority of the first and the second votes in 2009?’ required the participants to compare the first and the second votes within one election period. All questions were of the described format, only varying in the parties, the election periods, and the type of votes. Participants indicated their responses by marking one of the 19 answer options below the infographic.

Match/Mismatch trials. The combination of the two types of map organization and the two types of questions resulted in match and mismatch trials. In match trials, all information required for solving a task was visible within one map. Therefore, participants only had to identify the color of the party in question as well as the relevant map in match trials in order to subsequently count the states. In mismatch trails, however, the information required to solve a task was distributed between the two maps. Therefore, the participants also had to identify the color of the party as well as the relevant information; however, in these trials the relevant information was displayed as either the right bar or the left bar in both maps. Thus, the participants had to compare the bars in the two maps in order to count the states with consistent votes. Importantly, within the representation control condition, the participants were able to change the organization criterion of the maps. In this condition, the terms match and mismatch refer to the initial state of the maps.

Procedure

After providing informed consent, participants received instructions explaining the information extraction task. Participants in the representation control condition watched an additional instruction video that explained the condition-specific interactive functions. We instructed the participants only how the representation control features could be used in principle; however, we did not encourage them to use these features whenever applicable. Next, the participants completed four practice trials (two match and two mismatch trials), of which three had to be answered correctly. In case of more than one error, the practice trials were repeated until the criterion was met. Following these practice trials, the participants completed 24 experimental trials. One half of the trials consisted of match trials, the other half of mismatch trails. Match and mismatch trials alternated, the order being consistent among the participants. At the beginning of each trial, all information layers (types of votes and election periods) were visible.

In the representation control condition, participants could reorganize the maps by switching the organization criterion in an interaction menu on the left side of the screen (see Fig 1). Participants could also select and deselect information layers. In the static condition, no interaction menu was provided. In this condition, the participants solved the task based on the pair of maps without the option to reorganize and/or reduce information. The participants were allowed to change their response until they confirmed it and proceeded with the next trial.

Analysis

We analyzed response times (RTs) and error rates (ERs) as dependent variables. In the representation control group, we additionally analyzed changes to the map organization and the information density. The trials with a response time larger than four standard deviations from the mean (0.90%) were excluded from the analysis. Errors were dichotomously coded and the trials with inaccurate responses were ignored in all subsequent analyses. We used linear mixed effect models (LME) to analyze the log-transformed RTs (due to their leftward inclination). In order to analyze the ERs and layout changes, we used generalized linear mixed effect models (GLME) with the logit as link function.

Fixed effects in the RT and the ER analyses were condition (representation control vs. static), matching (match vs. mismatch), and the interaction between condition and matching. In the analysis of the changes of the layout, only the fixed effect matching was included in the model because layout changes were possible in the representation control condition only. All predictor variables were effect coded prior to analysis. In the models, we included a random intercept for each participant, as well as a random intercept for each task. The regression models were conducted using R [40] and the R packages lme4 [41], afex [42] and lmerTest [43] with Type 3 errors and Satterwaite approximation for degrees of freedom.

Results

Response time

The mean RTs for the representation control and the static condition across match and mismatch trials are depicted in Fig 2. The LME analysis revealed a significant interaction of

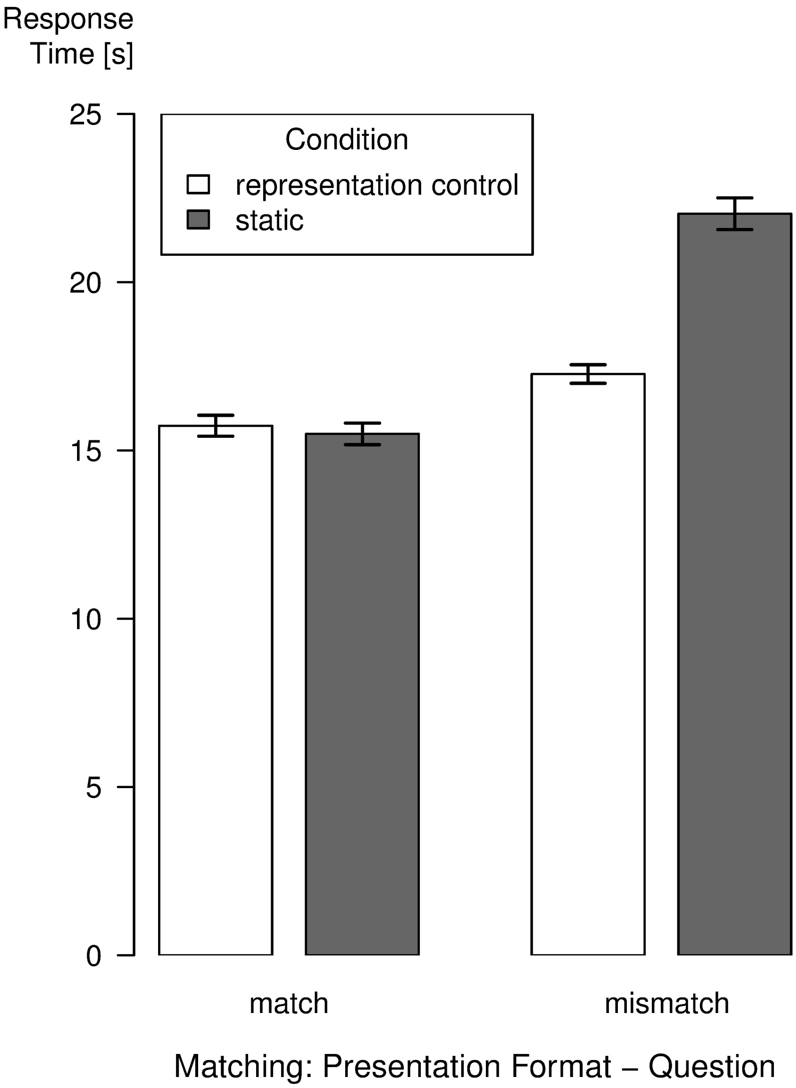

Fig 2. Mean response times for conditions as a function of matching between presentation format and question. Error bars represent standard errors.

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matching and condition, $\chi^2(1) = 81.71$, $p < .001$. Planned *t*-tests with Tukey adjustments for multiple comparisons confirmed that the RTs were faster in the representation control condition than in the static condition in mismatch trials only, $t(102.90) = -4.57$, $p < .001$, whereas there was no difference between the two conditions in the match trials, $t(100.06) = 0.19$, $p = 0.851$. Furthermore, the LME revealed a significant main effect for matching, $\chi^2(1) = 31.27$, $p < .001$ as well as a main effect for condition, $\chi^2(1) = 5.06$, $p = .025$.

Error rate

As depicted in Fig 3, error rates for the representation control and the static condition showed a similar pattern as the RTs. A GLME on ER revealed a significant interaction between the variables condition and matching, $\chi^2(1) = 8.15$, $p = .004$. The representation control condition and the static condition differed in mismatch trials, $z = 6.70$, $p < .001$, and also in match trials, $z = 3.55$, $p < .001$. Additionally, there was a main effect of condition, $\chi^2(1) = 33.78$, $p < .001$, whereas the main effect for matching did not reach significance, $\chi^2(1) = 0.91$, $p = .340$.

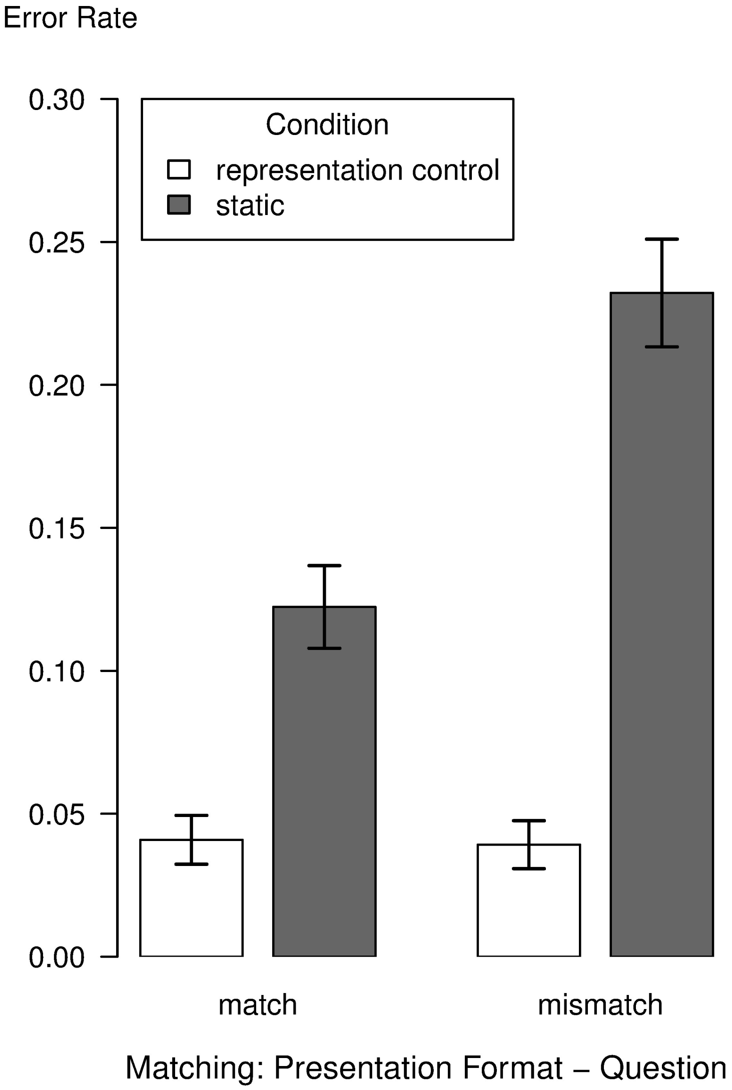

Fig 3. Mean error rates for conditions as a function of matching between presentation format and question. Error bars represent standard errors.

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Layout changes in representation control condition

Beyond RTs and ERs, we analyzed how frequently participants adjusted the spatial organization and information density in the representation control condition. Particularly, we were interested in whether these interactions differ for match and mismatch trials. For this purpose, we dichotomously coded whether the participants had adjusted the spatial organization of the graphical representation and/or the information density. The results are depicted in Fig 4.

Regarding the spatial reorganization, a GLME analysis revealed a significant effect of match vs. mismatch trials, $\chi^2(1) = 66.57$, $p < .001$. As depicted in Fig 4A, the graphical representations were reorganized in only 12% of the match trials, but in 80% of the mismatch trials. Regarding information reduction, the analysis revealed no main effect of matching, $\chi^2(1) = 0.76$, $p = .383$. The information density of the graphical representations was reduced equally often in match trials (73%) and in mismatch trials (74%; Fig 4B).

Discussion

The present experiment investigated whether task performance benefits from representation control in complex graphical representations. In line with our hypothesis, participants who

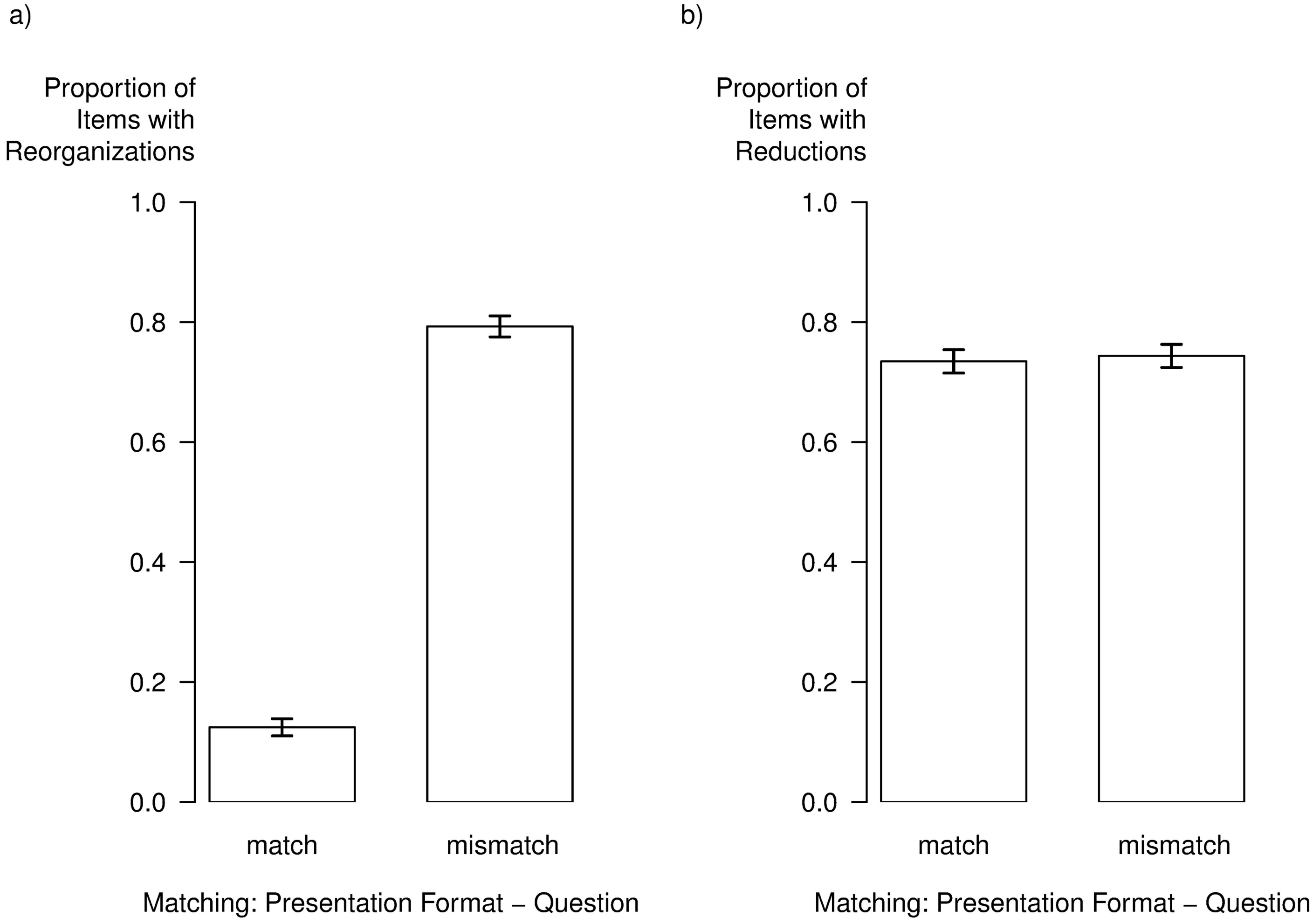

Fig 4. Proportion of items with a) spatial reorganizations and b) reduction of information density as a function of matching between presentation format and question in the representation control condition. Error bars represent standard errors.

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were able to alter the spatial organization of the presented information as well as to reduce information density of the graphical representation outperformed participants in the static group with respect to response time and accuracy. The beneficial effect of representation control was particularly pronounced in mismatch trials in which the relevant information for the question at hand was distributed across both maps. This is in line with our hypothesis that representation control is more beneficial in mismatch trials than in match trials as the option to reorganize the infographic is only useful in mismatch trials. Therefore, in mismatch trials, the participants could benefit from both transformations: the option to reduce information density and to reorganize the information, the former being in accordance with the coherence principle [44] and the latter in accordance with the spatial contiguity principle [44]. A more detailed analysis of the participants´ behavior within the representation control condition further corroborated this impression. As hypothesized, we observed reorganization of the depicted information more often in mismatch trials than in match trials. Thus, reorganization was used to adjust the spatial organization of information to the task requirements. In contrast, we observed reductions of the information density equally often in match and mismatch trials. This corroborates our hypothesis that reducing information density is useful in both types of trials. The high rate of reductions (>70%) is in accordance with former empirical results that demonstrated a benefit of sparse designs that only included relevant information [37], but contradicts the assumption of a preference for complex representations [4,38,39].

The differentiated pattern of usage of the two transformation functions of representation control–reducing information density in most match and mismatch trials and reorganizing information almost only in mismatch trials–represents a strategic, purposeful action that is executed with the aim to reduce task complexity. Consequently, participants of the representation control condition answered the questions in the mismatch trials faster and more accurately than participants in the static condition.

Our study provides evidence for the beneficial effects of the cognitive offloading of transformation processes [8]. Whereas a mental anticipation of spatial transformations is demanding with respect to mental effort, offloading such spatial transformations either in the environment [45] or into adjustments of one's own body orientation [11] typically increases task performance. To the best of our knowledge, this is the first study that has combined the concepts of cognitive offloading and of representation control. In the present study, we could thus demonstrate that cognitive offloading does not only apply to simple tasks such as reproducing or arranging visual patterns (e.g. pattern copy tasks or Tetris games, [7,12–14], but applies also to tasks that require the integration of such visual patterns in order to form complex aggregate judgments. For such tasks, representation control allows for cognitive offloading, thereby substantially increasing task efficiency. Importantly, participants did not apply representation control in just any case but used it in a highly strategic manner. Accordingly, we were able to specify conditions under which the use of representation control is likely to occur by conceptualizing it as an instance of cognitive offloading, which is characterized by weighing the cognitive ease of processing a given visual representation against the cognitive gains of rearranging it according to the task demands. In fact, by using representation control strategically, our participants showed a high level of *meta-representational competence* [4,46,47]. This competence involves the ability to anticipate possible representations, choose the best-fitting representation, and then adjust the graph accordingly. While Hegarty and colleagues [4] focused on choosing the best representation among various representations, the present study goes one step further by giving participants the option to adjust the representations according to the task requirements. Thereby, it combines the research on representation control with the research on cognitive offloading.

Overall, the findings of the study show that digital graphical representations offer a solution to the conflict between ease of use and usefulness. Designers may include information suitable for a wide range of tasks in a graphical representation, thus increasing its usefulness. At the same time, representation control allows the viewers themselves to interactively adapt a given graphical representation to task requirements, thus increasing its ease of use. Consequently, our participants spontaneously used representation control options in order to solve the information extraction task in an efficient manner.

Note that the present study was conducted with student participants. Almost all of them reported daily use of computers. Apart from their general knowledge of digital media, they were prepared to use the representation control by an instructional video and practice trials. In Germany and German speaking countries between 75 and 80% of the population above 14 years of age are using the Internet at least sometimes [48,49]. However, it is impossible to predict the effects of interactive features for the remaining 20–25% of the population without online experience. This should be investigated in a separate study especially because recent statistics show that individuals with lower education and elderly are overrepresented within the no/low media usage group [48,49]; see also [50].

Other inter-individual differences that we did not address in the present work are ability and metacognitive knowledge. As the aim of our study was to investigate whether representation control is used in infographics in order to offload cognitive processes and to test the effects thereof, we did not measure metacognition nor the abilities of our participants. Instead, we used a rather large and homogeneous sample to minimize individual influences. However, former studies found an influence of ability and metacognitive evaluations on offloading behavior [18,16]. Risko and Gilbert [8] propose a model of the underlying processes. Future studies on the influence of task-specific abilities and metacognitive knowledge on the usage of representation control are therefore desirable.

In the present experiment, we allowed our participants to change the spatial organization and to reduce the information density. These two transformations were selected based on theoretical assumptions and allowed us to investigate the effect of representation control in a controlled experimental setup. A closer look at recent interactive infographics and maps makes clear that the options for how representation control could be implemented are manifold [51]. For example, it may allow for adding more layers of relevant information instead of eliminating unnecessary information. It may also allow for splitting a single map into several separate units instead of reorganizing relevant information into a single map. Given the close relationship of representation control with cognitive offloading that we have postulated in the present article, these types of interactive modifications should also be governed by principles of cognitive offloading. Yet, this generalization of the present findings along with its boundary conditions certainly has to be investigated in future empirical studies.

The main part of the interactive infographics that we used in the present study consisted of pairs of maps. In a recently published research agenda, Roth and his colleagues [51] identified 17 opportunities for empirical research on interactivity in maps and visualizations. Among these are included the opportunity to develop strategies to compare static and interactive maps or the opportunity to investigate the value of interactivity in new map use cases. Both are addressed in our study. Also, in visual analytics and information visualization research, interaction is an important concept [52]. Even though this field of research focuses more on knowledge construction than on information communication, some of the challenges that were identified in information visualization (e.g. capturing user intentionality) also generalize to the use of infographics for communication purposes–at least if interactive features are implemented in infographics.

The present findings demonstrate how cognitive offloading, spatial contiguity, and information coherence may inform the design of interactive knowledge media that is intended for a broad and diverse group of recipients. Particularly in online media as well as in informal educational settings in which the information goals vary across individuals, well-designed interactive features may contribute to resolve the conflict between ease of use and usefulness of complex graphical representations such as infographics or maps.

Author Contributions

Conceptualization: Claudia Meyer-Dernbecher, Stephan Schwan.

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Funding acquisition: Stephan Schwan.

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Appendix C

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Control Over Spatial Representation Format Enhances Information Extraction But Prevents Long-Term Learning

Short Title:	Information Extraction And Long-Term Learning With Representation Control
Keywords:	Representation Control, Incidental Learning, Visualizations, Cognitive Offloading
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Abstract

Previous research has demonstrated that cognitive offloading (i.e. externalizing mental processes) is useful for immediate problem solving. However, long-term effects of cognitive offloading on subsequent problem solving without offloading are remarkably understudied. Our main goal was to investigate the effects of representation control (i.e. adjusting the format of the representation to task requirements) on incidental procedural learning in an information extraction task with interactive visualizations. More specifically, we tested how the availability of representation control for solving tasks in a practice phase affects procedural learning measured in a testing phase in which representation control is no longer available. In both phases, we explored time on task as well as proportion correct as proxies of task performance and analyzed how often participants used representation control. We conducted three experiments in which participants could modify and reorganize information displays in the practice phase, whereas in the testing phase, they had to solve equivalent and near transfer problems without this offloading opportunity. We show that representation control is beneficial for immediate task solution, particularly for problems that require a spatial transformation. This benefit was more pronounced for automated (i.e. system-controlled) types of control (Experiment 3). In contrast, in subsequent problem solving without representation control (up to 24 hours later), participants who had been using representation control previously fell back to the level of an untrained baseline condition (Experiments 1 and 2). However, the detrimental effect of representation control was confined to equivalent tasks and did not generalize to a near transfer task.

Educational Impact and Implications Statement

Interactive types of visualizations have become an important form of learning material, both in schools and in higher education. While previous studies of interactive control of visual representations have focused mainly on their immediate effects on acquisition of learning contents (*effects with* representation control), the present demonstrates the detrimental long-term effects of the use of representation control on learning procedural tasks (*effects of* representation control) if this control feature is no longer available to the learner. We further show that reducing active representation control while still visually demonstrating the required procedural steps may substantially reduce the observed detrimental effects. Therefore, in line with the desirable difficulties approach, the distinction between *effects with* and *effects of* representation control may serve as a model to guide the implementation of interactive features for visualizations in learning materials.

Keywords

Representation Control; Incidental Learning; Visualizations; Cognitive Offloading

Introduction

Humans have developed a great number of external tools that ease the solving of cognitive tasks, ranging from paper and pencil to calculators and digital navigation systems. In principle, these devices allow for externalizing or offloading certain content and/or procedures from working memory, thus substantially reducing the cognitive requirements for solving a given task (Kirsh & Maglio, 1994; Risko & Gilbert, 2016; Scheiter, 2014). However, from a learning perspective, it is an open question how the repeated use of an external tool influences problem solving in subsequent situations in which the tool is no longer available (Fenech, Drews, & Bakdash, 2010; Salomon & Perkins, 2005; Salomon, 1990). In other words, it is unclear what effects cognitive offloading has on subsequent performance while typically boosting immediate task performance. Cognitive offloading could either help or hinder learners to acquire the underlying cognitive routines that are necessary for successful problem solving without having the tool at hand. Whereas the desirable difficulties approach (Bjork & Bjork, 2011) indicates that facilitating performance during the acquisition phase of learning tasks bears the risk of reduced learning outcomes, other approaches suggest that externalizing cognitive steps might foster procedural learning instead (Salomon, 1990). In order to address this question, we conducted three two-phased experiments in which the opportunity to modify and reorganize information displays in order to solve specific problems varied between the two phases. That means that most of the participants had to solve structurally equivalent problems, in one phase with and in the other phase without an offloading opportunity.

Cognitive Offloading, Epistemic Actions, and Representation Control

The concept of human cognition has changed in the past decades from a notion of the human as a discrete information processor towards a system-based approach. Humans are no longer seen as individuals who process information independently of their environment.

Instead, they are seen as embedded in a system consisting of their own body, other people, objects, tools, and the surrounding space (Choi, van Merrienboer, & Paas, 2014; Parsons & Sedig, 2011). This perspective of the extended mind (Clark & Chalmers, 1998) states that the human cognition goes beyond the mind itself, implying that information processing as well as memory storage can be offloaded into the external environment (Cary & Carlson, 1999; Gray, Sims, Fu, & Schoelles, 2006; Kirsh & Maglio, 1994). Cognitive offloading thereby allows for overcoming the internal limitations in information processing and memory capacity. Thus, cognitive offloading is capable of enabling and facilitating task solution (e.g. Carlson, Avraamides, Cary, & Strasberg, 2007; Chu & Kita, 2011; Gilbert, 2015; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Risko, Medimorec, Chisholm, & Kingstone, 2014).

As one important type of cognitive offloading, overt actions may be used to replace certain steps of cognitive processing in tasks that otherwise would require anticipating the results of equivalent transformations mentally (Kirsh & Maglio, 1994). Primarily, such epistemic actions serve to reduce memory load or the amount of information processing, thereby reducing the probability of processing errors (Kirsh, 2010; Scaife & Rogers, 1996). For instance, Kirsh and Maglio (1994) observed that Tetris players use the option to rotate and translate the falling blocks not only in order to fit them into the layout but also to avoid the mental anticipation of the outcome of these actions.

Subsequent research on science learning relied on the concept of epistemic actions in order to explain the role of learners' overt manipulation of physical models or visual representations for knowledge acquisition (Kastens, Liben, & Agrawal, 2008). Particularly, in visual representations such as maps, graphs, charts, or animations, epistemic actions bear a strong resemblance to representation control that has been discussed in the context of multimedia learning. Representation control allows the learner to adjust the format of the representation to the requirements of the task at hand (Scheiter, 2014). Representation control thus serves for offloading cognitive transformations into visual representations. In analogy to epistemic actions, adjusting visual representations enables the externalization of mental transformations and therefore reduces the amount of cognitive processing that is necessary for solving a particular task. According to Kirsh (1995), such adaptions may include removing, clustering, ordering, reorienting, or juxtaposing elements of the information display. Consequently, if users take advantage of representation control to adapt the superficial organization of a visual representation such as an interactive infographic appropriately, certain task relevant information may be much easier to process.

At the same time, however, representation control also implies additional cognitive demands. The user has to define the relevant information in order to decide which display format is most adequate for the task and then transform the visual representation accordingly. However, users do not just need to possess sufficient knowledge about the task in order to choose the appropriate epistemic activities. This comes along with a trade-off between the allocation of mental resources to internal processes in order to solve a task mentally without externalization or the allocation of resources to processes of planning and executing the externalization of the cognitive operations. Therefore, users should only take the opportunity for epistemic actions if it reduces the required cognitive resources in sum. This is the case either if the mental solution is highly demanding or if planning and executing the beneficial epistemic actions requires minimal cognitive resources, or both. Indeed, this trade-off between effort spent on covert mental versus overt external activities for task accomplishment has been demonstrated in several studies. Increasing the costs of epistemic actions in terms of time or energy comes along with a higher probability of solving a task mentally without externalization (Cary & Carlson, 1999; Gray et al., 2006; Schönpflug, 1986).

Trade-off Between Task Accomplishment and Procedural Learning

According to the desirable difficulties approach, high performance in the learning phase does not necessarily imply a long-term increase in comprehension or skill acquisition

(Soderstrom & Bjork, 2015). Instead, learners often benefit from more demanding tasks although they show a lower performance initially. Therefore, providing representation control might foster immediate task performance but may be detrimental to procedural learning. While the concept of desirable difficulties has been developed in the context of explicit learning intentions (e.g. Yue, Bjork, & Bjork, 2013), similar effects may also occur under conditions of incidental learning. In other words, the acquisition of knowledge might arise as a byproduct of mere exposure to or interaction with a specific content without an explicit learning intention (Marsick & Watkins, 2001). There is some empirical evidence that cognitive offloading might lower incidental learning of procedural knowledge (e.g. van Nimwegen & van Oostendorp, 2009). For instance, the acquisition of route knowledge is less pronounced when using navigational aids (such as turn-by-turn auditory instructions; Fenech et al., 2010; Gardony, Brunyé, Mahoney, & Taylor, 2013; Gardony, Brunyé, & Taylor, 2015). Similar effects have also been reported for skill retention and procedural knowledge in military and medical contexts or in aviation (e.g. Kluge & Frank, 2014). The correct execution of these skills is highly relevant in emergencies; however, increasing automation has resulted in a decay of these skills (e.g. Casner, Geven, Recker, & Schooler, 2014; Ebbatson, Harris, Huddlestone, & Sears, 2010). Taken together, these empirical results suggest that cognitive offloading might deteriorate performance in a subsequent identical task when offloading is no longer possible.

Salomon and Perkins (2005) have proposed a more sophisticated model which predicts both positive and negative learning effects of cognitive offloading, depending on the specific relation between the external cognitive tool and the learning task. They distinguish between effects *with*, *of,* and *through* technology. Whereas effects *with* technology refer to changes in intellectual performance *during* the use of technology (e.g., cognitive offloading or epistemic actions), effects *of* technology refer to changes in cognitive performance *after* the use of technology (i.e. without the tool). The third type of effects is the effect *through* technology that refers to the fundamental reorganization of performance through technology.

Regarding effects *of* technology on learning, Salomon (1974, 1979, 1990) assumes that media - as one important class of offloading tools - can explicitly model cognitive operations and processing steps that are necessary to solve a task. Hence, the use of media should result in enhanced knowledge acquisition as it facilitates task solving by explicitly demonstrating the required processing steps. This allows for internalizing the underlying structure of the tasks and thus prepares the user for tasks in which the media is no longer available (*modeling* cf. Salomon, 1979). However, detrimental effects might arise if the medium either models processes as well as procedural steps that are not applicable in cases in which the medium is not at hand or if the model does not demonstrate the necessary procedural steps by just showing the final state of the otherwise stepwise transformation (*short circuit* cf. Salomon, 1979). Additionally, the positive effects of external modeling presuppose that offloading results in an increased amount of free cognitive resources that allow for deeper and more elaborate processing, which in turn leads to enhanced learning (Salomon, 1990; Sweller, van Merrienboer, & Paas, 1998).

However, as discussed in the previous paragraph, a possible gain from freeing cognitive resources depends instead on the costs (planning and execution) of externalizing the mental processes. Studies exploring effects of learner control in the field of multimedia learning have shown that the latter may outweigh the former what might result in a net decrease in learning and comprehension (Lunts, 2002; Scheiter, 2014; Scheiter & Gerjets, 2007; Schnotz & Rasch, 2005).

To sum up, providing users with the option to reorganize or simplify a given visual representation according to task requirements can be considered a typical instance of epistemic action or representation control. Representation control allows for offloading covert processing steps from working memory by turning them into overt actions, thus boosting task efficiency (Moritz, Meyerhoff, Meyer-Dernbecher, & Schwan, 2018). While previous research has demonstrated that *effects with* representation control are beneficial for solving a task, the *effects of* representation control on procedural learning and subsequent task performance are not yet understood.

Following Salomon and Perkins (2005), controlling and adjusting the format of a given visualization in a manner that provides a better fit with the task at hand might facilitate learning to perform the task for two reasons. First, the adjustments of the visualization may saliently demonstrate processing steps that the learner would need to go through if the task had to be solved mentally. In other words, *effects with* representation control might enhance procedural learning and subsequent task performance if the users translate overt reorganization and simplification of a given visual representation into corresponding covert cognitive steps (Salomon, 1994). Second, simplifying the task by adjusting the visualization might free some cognitive resources that may be used for deeper understanding the underlying task structure. In contrast, following the notion of desirable difficulties, *effects of* representation control might decrease subsequent task performance without the tool if the users develop skills for efficient usage of the tool but do not acquire the cognitive processing steps that are required for solving the task itself (Fenech et al., 2010; Gardony et al., 2013, 2015).

Research Question and Hypotheses

The main goal of our three experiments was to investigate how the availability of representation control for solving a set of information extraction problems in a practice phase affects procedural learning measured in a testing phase in which representation control is no longer available. In both phases, we explored the time on task as well as the proportion correct as proxies of task performance and analyzed how often participants used representation control.

In Experiment 1, we implemented a representation control condition in which participants first practiced a set of information extraction problems with the opportunity to interactively reorganize a given visualization according to the task demands (practice phase). Subsequently, they solved a set of structurally equivalent problems without representation control (testing phase). The participants' performance was compared to both a condition in which participants solved the task without representation control in both phases (no representation control condition) and to a baseline condition in which participants completed the testing phase only.

For the practice phase, we hypothesized that the participants with representation control outperform the participants without representation control due to effects of cognitive offloading. This should be especially apparent in situations in which the initial arrangement of information in the visualization does not match the task requirements. Depending on the learning process, there are two possible outcomes of the testing phase without representation control in any condition. On the one hand, if the users acquire the cognitive steps from the overt reorganizations and simplifications during the phase with representation control, we should observe enhanced task performance during the testing phase. On the other hand, if the users acquire the ability to use representation control rather than the cognitive processes, we should observe a drop in performance (relative to the no representation control condition) when representation control is no longer available.

In Experiment 2, we aimed at replicating and extending the findings of Experiment 1. Further, we investigated the effect of representation control on incidental learning with a stronger focus on long-term effects (i.e. a retention interval of one day) as well as near transfer (i.e. to similar but not identical problems). In this experiment, we also intended to rule out any explanations arising from compatibility effects. Therefore, we implemented four conditions that fully crossed the availability of representation control in the practice phase and the testing phase - including a near transfer part. For the practice phase, we hypothesized - in accordance with Experiment 1 - that the participants with representation control outperform the participants without representation control due to effects of cognitive offloading. This should be especially apparent in situations in which the initial arrangement of information in the visualization does not match the task requirements. For the testing phase, we expected - based on the results of Experiment 1 - that the participants only acquire the ability to use representation control rather than the cognitive processes, and therefore, we expected to observe a drop in their performance both in a reproduction and in a near transfer problem solving task (relative to the no representation control condition) when representation control is no longer available after a delay of one day.

Based on the approach by Salomon and Perkins (2005), Experiment 3 focused on the role of the presentation of the reduced information during the representation control and thus compared three types of representation control: an active representation control condition, a modeling condition in which all necessary steps were visibly executed, and a short-circuit condition showing only the final state without intermediate steps. Additionally, we again ran a baseline condition in which participants completed the testing phase only.

For the practice phase, we hypothesized that immediate task performance increases with an increasing automatization of the reorganization process. The performance in the short-circuit condition should therefore be superior to the performance in the modeling condition which in return should be superior to the performance in the active representation control condition. For the testing phase, we hypothesized that the modeling condition would free the participants from the requirements of planning and executing the reorganization process. Thus, the modeling condition allows the participants to better observe, memorize, and thereby internalize the respective processing steps, leading to an enhanced performance of this condition in the testing phase. In contrast, this benefit of observation should be absent in the short-circuit condition in which only the final state of the transformation of the visualization appears onscreen.

Experiment 1

Methods

Participants.

One hundred and twenty participants (M = 23.66 years, range 18-34 years, 92 females, no color impairments of vision) were recruited from the local participant pool of our research center. They were randomly assigned to the three conditions. The experimental procedure was approved by the ethics committee of our research center. All participants gave informed consent prior to testing.

Apparatus and materials.

The experiment was conducted on Microsoft Surface Pro2 tablets with a 10.6-inch screen (1920 x 1080 pixels). Responses were recorded using the touch-sensitive display. The information graphics consisted of two maps that were arranged side-by-side. Both maps depicted the same fictitious country consisting of 18 districts. The maps showed the result of two elections for two types of votes. Within each district, two colored bars indicated the winner's party (see Fig. 1). The two types of votes were called first and second vote (inspired by the German election system).

Fig 1. Illustration of the Information Graphics Used in all Three Experiments. The maps were initially organized (a) by type of vote or (b) by election period. Interactive reorganization was possible only in the conditions with representation control. Only in these conditions, the interaction menu (left) was present.

In one half of the trials (counterbalanced within participants), the visualization was initially organized by election period (i.e. the 2009 election on the left side and the 2013 election on the right side). In the remaining half of the trials, the visualization was initially organized by the type of votes (i.e. the first votes on the left side and the second votes on the right side).

For each visualization, the participants solved one task based on the depicted information. This task focused on a comparison either between the two types of votes for a given election period or between the two election periods for a given type of vote. For instance, the question “In how many election districts did the party SVP gain the majority of first votes in both 2009 and 2013?” focused on a comparison of the first votes between the two election periods, whereas the question “In how many election districts did party SVP gain the majority of first and second votes in 2009?” focused on a comparison between the types of vote for one election period. The combination of the two map organizations and the two task foci resulted in match and mismatch trials: In match trials, the task could be solved with the information depicted in one of the two maps, whereas mismatch trials required information from both maps. In practice, the participants had to identify the color of the relevant party in both types of trials. After that, they had to identify the bars at the corresponding locations either within one of the maps (match trials) or across the maps (mismatch trials). The participants indicated their responses by marking one of the 19 answer options below the visualization. They were allowed to change their response until they confirmed their selection by pressing onto a proceed button (i.e. the task was self-paced). The participants in the representation control condition could reorganize the graphic (i.e. altering between the two organizations of the maps) or reduce information density (i.e. eliminating information) with the corresponding menu on the left side of the screen (see Fig. 1). This menu was not present in the condition without representation control. Importantly, the terms match and mismatch describe the initial organization of the visualization prior to any self-initiated changes in the spatial organization of the maps.

Procedure.

At the beginning of the experiment, the participants received instructions regarding the visualization as well as the task. The participants were asked to solve the tasks as accurately and as fast as possible. Additionally, the participants in the representation control condition watched an instructional video that showed how to use the interactive features of the visualization. Following this, the participants completed four practice trials of which three had to be answered correctly. The participants who did not meet this criterion were required to repeat the practice trials. The practice and the testing phase of the experiment consisted of 24 trials each. Whereas the interaction features differed between the conditions in the practice phase, all participants had to solve the tasks without representation control in the testing phase (i.e. the interactive features of representation control were removed during this phase). Furthermore, we added another baseline condition in which the participants completed only the testing phase of the experiment in order to obtain a proxy for untrained performance. The experiment lasted 45 minutes for each phase.

Analysis.

We analyzed the time on task as well as proportion correct as dependent variables. Additionally, we analyzed whether or not the participants within the representation control condition used the interactive features during the practice phase. Time on task was measured from the onset of the presentation of the visualization until the confirmation of the response through the proceed button. Trials with a time on task larger than four standard deviations from the mean were excluded from the analysis (0.90%). Errors were dichotomously coded and trials with inaccurate responses were ignored in the analysis of the time on task. We log-transformed the time on task due to its leftward inclination. We used linear mixed effect models (LME) to analyze the log-transformed time on task and generalized linear mixed effect models (GLME) with the logit as a link function to analyze the proportion correct and the layout changes. Fixed effects in the analyses of the time on task and proportion correct were condition (representation control vs. no representation control) and matching (match vs. mismatch) and the interaction between condition and matching.

In the analysis of the use of the interactive features in the representation control condition, we only included matching as a fixed effect. Predictor variables were effect coded prior to the analysis. We included a random intercept and random slope for matching per participants and a random intercept for each visualization in all models. The regression models were conducted using R (R Development Core Team, 2015) and the R packages lme4 (Bates, Mächler, Bolker, & Walker, 2015), lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017), car (Fox & Weisberg, 2019) and afex (Singmann, Bolker, Westfall, & Aust, 2016), with Type 3 errors and Satterthwaite approximation for degrees of freedom.

Results

Practice Phase.

Time on Task.

The LME analysis of the log-transformed time on task revealed a significant interaction of matching and condition, $\chi^2(1) = 54.99$, $p < .001$ (see Fig. 2a). Planned *t*-tests with Tukey adjustments for multiple comparisons indicated that the time on task was shorter in the representation control condition than in the no representation control condition in mismatch trials, $t(78.01) = -6.56$, $p < .001$, whereas the time on task in the representation control condition and in the no representation control condition did not differ in match trials, $t(78.03) = -1.27$, $p = 0.207$. Furthermore, the LME analysis revealed a significant main effect of matching, $\chi^2(1) = 63.21$, $p < .001$ as well as a significant main effect of condition, $\chi^2(1) = 15.32$, $p < .001$.

Fig. 2: Results of the Practice Phase of Experiment 1. a) Time on Task in Seconds, b) Proportion Correct. Error bars represent the standard error of the mean.

Proportion Correct.

A GLME analysis on the proportion correct only revealed a significant main effect of condition, $\chi^2(1) = 18.69$, $p < .001$ (see Figure 2b). Participants in the representation control condition committed fewer errors than participants in the no representation control condition. Neither the main effect of matching, $\chi^2(1) = 0.70$, $p = .404$, nor the interaction of matching and condition reached significance, $\chi^2(1) = 0.72$, $p = .397$.

Use of interactive features.

The GLME analysis revealed a significant effect of matching on reorganization, $\chi^2(1) = 36.09$, $p < .001$. In accordance with the optimal solution of the tasks, visualizations were reorganized in 93% (*SD* = 25%) of the mismatch trials but only in 6% (*SD* = 24%) of the match trials. Because reducing information density was generally helpful for task solution, the participants reduced information density equally often in match (*M* = 58%, *SD* = 49%) and mismatch trials (*M* = 59%, *SD* = 49%), $\chi^2(1) = 0.58$, $p = .446$.

Testing Phase.

Time on Task.

The LME on the log-transformed time on task for the testing (non-interactive) phase revealed a significant interaction of matching and condition, $\chi^2(2) = 12.13$, $p = .002$, indicating that the influence of the conditions differed between match and mismatch trials (see Figure 3a). For mismatch trials, planned *t*-tests with Tukey adjustments for multiple comparisons indicated that there was no difference between the time on task in the representation control condition and in the baseline condition without practice, $t(116.53) = -$

1.81, $p = .172$. Importantly, the time on task in this baseline condition without practice was substantially longer than in the no representation control condition, $t(117.32) = 3.93$, $p < .001$. The time on task in the representation control condition did not differ significantly from the time on task in the no representation control condition, $t(115.84) = 2.14$, $p = .087$. However, it was numerically longer than the time on task in the no representation control condition and showed the reversed pattern compared to the practice phase. In match trials, the time on task also did not differ between the representation control condition and the no representation control condition, $t(116.13) = -0.10$, $p = .995$, but the time on task in the representation control condition, $t(116.73) = -3.66$, $p = .001$, as well as in the no representation control condition, $t(117.74) = -3.56$, $p = .002$, was shorter than the time on task in the baseline without practice.

The LME revealed furthermore a significant main effect of matching, $\chi^2(1) = 60.26$, $p < .001$. In match trials, the time on task was shorter than in mismatch trials. In addition, the main effect of condition also reached significance, $\chi^2(2) = 17.06$, $p < .001$.

Figure 3. Results of the Testing Phase of Experiment 1. a) Time on Task in Seconds, b) Proportion Correct. Error bars represent the standard error of the mean.

Proportion Correct.

The GLME revealed a main effect of matching on proportion correct $\chi^2(1) = 15.79$, $p < .001$, indicating that responses were more accurate in match than in mismatch trials (see Fig. 3b). Despite differing numerically, the condition had no effect on proportion correct, $\chi^2(2) = 5.11$, $p = .078$. Also, the interaction of matching and condition did not reach significance, $\chi^2(2) = 2.27$, $p = .322$.

Discussion

The first experiment investigated the *effects with* representation control in the practice phase as well as the *effects of* representation control on performance in the testing phase. In line with our hypothesis, the results of the practice phase indicate that the users weighted the cognitive gains of reorganizing the visualization according to the task demands against the cognitive costs of planning and executing the reorganizing process. Accordingly, representation control was heavily used for mismatch trials in which the spatial organization of the visualization did not correspond to the task requirements, whereas representation control was used to a lower degree for match trials in which the spatial organization of the visualization did correspond to the task. As a result, the participants in the representation control condition outperformed (i.e. faster and more accurate solutions) those in the no representation control condition, particularly in mismatch trials. Hence, the findings from the practice phase support the view that representation control fosters problem solving.

Importantly, this benefit of the representation control condition disappeared when representation control was no longer available in the testing phase. More specifically, the participants in the representation control condition fell back to the level of an untrained baseline condition for mismatch items. This indicates that they did not acquire knowledge about the underlying structure of the task to a sufficient degree if they relied on epistemic actions in order to reorganize the visualization according to the task demands in the practice phase of the experiment. In contrast, the participants were more efficient (i.e. faster solutions at an equal level of accuracy) than the participants in the untrained baseline condition in tasks that were solved primarily by covert mental processing in the practice phase, thus demonstrating a substantial learning effect. This was the case for match trials in the representation control condition as well as for both match and mismatch trials in the no representation control condition.

Experiment 2

In Experiment 1, we showed that representation control fostered problem solving during a practice phase, but this benefit disappeared when representation control was no longer available in a subsequent testing phase. However, the temporal delay between the two phases was only 20 minutes. Furthermore, the problems were equivalent in both phases and did not allow for testing possible effects of transfer. The purpose of this experiment was to investigate whether the results of Experiment 1 generalize to a longer time delay and to a near transfer task. Additionally, we wanted to rule out the possibility that the poorer results of the representation control condition only appeared due to a compatibility effect as the interactive options differed between the two phases. In Experiment 2, we therefore extended the temporal delay between the practice and the testing phase from 20 minutes to one day and redesigned the testing phase in which the participants solved equivalent as well as near transfer problems. Additionally, we fully crossed the availability of representation control in both phases, resulting in four conditions: participants who could use representation control in both phases, participants who could use representation control either only during the practice or only during the testing phase, and participants who could not use representation control at all. As in Experiment 1, we explored time on task as well as proportion correct in both the practice phase and the subsequent testing phase. In the representation control cases, we also analyzed how often our participants used the interactive features.

Methods

Participants.

The final sample consisted of 161 participants (mean age: 23.02 years, range 18-31 years, 123 females) recruited from the local participant pool of our research center. They were randomly assigned to one of the four conditions. The experimental procedure was approved by the ethics committee of our research center. All participants gave written informed consent prior to testing. No participant reported color impairment.

Apparatus and materials.

Apparatus and materials were the same as in Experiment 1 with the following exceptions. First, we systematically varied the availability of representation control (representation control vs. no representation control) in both phases in a fully crossed 2 x 2 between subjects design. Within this design, we replicated the representation control condition of Experiment 1, in which the participants had access to representation control only during practicing (rc-nrc) as well as the no representation control condition, in which the participants had no access to representation control at all (nrc-nrc). Further, we included a condition in which participants had access to representation control both during practice and testing (rc-rc) as well as a condition in which the participants had access to representation control only during the testing phase but not during practice (nrc-rc).

An additional difference to Experiment 1 was the initial spatial organization of the visualization. In Experiment 2, all visualizations of the practice phase were organized according to the same criterion: for one half of the participants by election period, for the other half of the participants by type of vote. The testing phase was split into a reproduction part consisting of a test of equivalent problems and a near transfer part. Equivalent problems were spatially organized according to the same criterion as the visualizations in the practice phase. In the near transfer part, the visualizations were organized by the complementary criterion. For instance, if a participant had visualizations available that were organized according to the type of vote during the practice phase, equivalent problems of the reproduction part were also organized by the type of vote. In contrast, the near transfer test would then be organized according to the election period for this participant. The aim of the separation was to differentiate between the reproduction of formerly learned solutions and the near transfer of these solutions to another task that is structurally similar but differs in the organization of its surface appearance.

Procedure.

The procedure was similar to that of Experiment 1, but we extended the time delay between practicing and testing to one day (approx. 24 hours). The participants watched at the beginning of both phases an instructional video that explained the task and the condition-specific interactive features of the visualizations before the phases started.

Analysis.

Data preparation was identical to Experiment 1. Again, we excluded trials with a time on task that was more than four standard deviations above the mean time on task as well as trials with a time on task faster than 3000 ms (1.11% of all trials). The analysis procedure differed slightly as we were not only interested in comparisons between conditions but also between practice phase and reproduction phase. Therefore, we included the data from both phases into a single analysis. This was possible because in Experiment 2 all participants completed both phases. Pairwise comparisons were conducted using the emmeans package of R with mvt adjustment (using the multivariate *t*-distribution) for multiple comparisons. Additional analyses were run on the time on task and proportion correct for the transfer phase. In addition to the analyses of the time on task and proportion correct, we conducted GLME analyses on the use of representation control. For each of its dependent variables (reorganizing and reduction), we ran three analyses, separately for the practice phase, the reproduction phase, and the transfer phase. We included matching and condition as fixed effects in the model[1]. In the analysis of the reduction of information density, we excluded 55

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[1] Please note that the random effect structure varied in these models in order to allow the models to converge.

trials in which the participant eliminated the irrelevant information only partially or some of the relevant information.

Results

Time on task during practicing and reproduction.

As shown in Figures 4a) and 5a), the time on task in solving mismatch trials increased from practicing to testing for the group that had practiced with the aid of representation control if tested without access to representation control, resulting in a longer time on task than the group that had no previous access to representation control.

Replicating the pattern of Experiment 1, the LME analysis of the log-transformed time on task revealed a significant three-way interaction of matching, condition, and phase, $\chi^2(3) = 170.13$, $p < .001$, indicating that the influence of condition differed between match and mismatch trials in the two phases (see Fig. 4a and 5a). All other lower-order interactions as well as main effects also reached significance (see Tab. 1). In order to qualify the interactions, we will first report contrasts for the match trials followed by the contrasts for the mismatch trials.

Insert Table 1 here

In match trials, groups with representation control (rc-rc and rc-nrc) showed longer time on task than participants who did not have representation control at hand (nrc-rc and nrc-nrc) during the practice phase, $z = 3.62$, $p < .001$, with no differences between the two groups with representation control (rc-rc and rc-nrc, $z = -0.61$, $p = .928$) and between the two groups without representation control (nrc-rc and nrc-nrc, $z = 1.11$, $p = .685$). For the testing phase, no differences between the conditions were found for the time on task in the reproduction task, all $|z| \leq 2.53$, $p \geq .056$. Participants in all conditions improved from practicing to reproduction in match trials (for rc-rc: $z = 4.49$, $p < .001$; for rc-nrc: $z = 3.91$, $p < .001$; for nrc-rc: $z = 2.93$, $p = .003$; for nrc-nrc: $z = 3.17$, $p = .002$).

Figure 4. Results of Experiment 2 for the Practice Phase. a) Time on Task in Seconds, b) Proportion Correct. Error bars represent the standard error of the mean. rc: representation control; nrc: no representation control.

For mismatch trials, a more complex pattern was found. In the practice phase, the time on task was shorter with representation control than without it (rc-rc / rc-nrc vs. nrc-rc / nrc-nrc), $z = -5.04$, $p < .001$, with no differences between the two groups with representation control (rc-rc and rc-nrc, $z = -0.76$, $p = .872$), and between the two groups without representation control (nrc-rc and nrc-nrc, $z = -0.06$, $p = 1.000$). In the testing phase, the time on task in the reproduction task was shorter with representation control during testing than without it (rc-rc / nrc-rc vs. rc-nrc / nrc-nrc), $z = -8.03$, $p < .001$. While the time on task for the two groups with representation control during testing (rc-rc and nrc-rc) was comparable, $z = -1.57$, $p = .398$, a comparison between the two conditions without representation control during testing revealed that the time on task for the group that had practiced before without representation control (nrc-nrc) was shorter in mismatch trials than for the group that had practiced with representation control beforehand (rc-nrc), $z = 4.10$, $p < .001$.

Figure 5. Results of Experiment 2 for the Reproduction Phase. a) Time on Task in Seconds, b) Proportion Correct. Error bars represent the standard error of the mean. rc: representation control; nrc: no representation control.

Finally, the time on task in two groups - with representation control during the two phases as well as without representation control during the two phases - decreased from practicing to testing for mismatch trials (for rc-rc: $z = 3.77$, $p < .001$; for nrc-nrc: $z = 3.09$, $p = .002$). The same was true for those participants who changed from practicing without the aid of representation control to testing with representation control (nrc-rc: $z = 5.85$, $p < .001$).

Most importantly, however, time on task in solving mismatch trials increased for the group that had practiced with the aid of representation control if tested without access to representation control ($z = -3.94$, $p < .001$).

Time on task during transfer.

As shown in Figure 6 a), groups with representation control in the testing phase (rc-rc and nrc-rc) showed a shorter time on task for transfer tasks than participants who did not have representation control at hand in that phase (rc-nrc and nrc-nrc). The LME analysis of the log-transformed time on task revealed a significant interaction of matching and condition, $\chi^2(3) = 115.39$, $p < .001$, indicating that the influence of condition differed between match and mismatch trials (see Fig. 6a). The main effect of matching ($\chi^2(1) = 224.44$, $p < .001$) and the main effect of condition also reached significance, $\chi^2(3) = 42.60$, $p < .001$. As in the previous section, we will first report the contrast for the match trials followed by the contrast for the mismatch trials in order to qualify the interaction.

In match trials, groups with representation control in the testing phase (rc-rc and nrc-rc) showed a shorter time on task for transfer tasks than participants who did not have representation control at hand in that phase (rc-nrc and nrc-nrc), $t\ (164.19) = -2.30$, $p = .023$, with no differences between the two groups with representation control (rc-rc and nrc-rc, $t\ (162.75) = -1.07$, $p = .711$) and between the two groups without representation control (rc-nrc and nrc-nrc, $t\ (165.67) = 0.36$, $p = .983$).

In mismatch trials, groups with representation control in the testing phase (rc-rc and nrc-rc) showed a shorter time on task for transfer tasks than participants who did not have representation control at hand in that phase (rc-nrc and nrc-nrc), $t\ (164.56) = -10.39$, $p < .001$, with no differences between the two groups with representation control (rc-rc and nrc-rc, $t\ (158.36) = -0.69$, $p = .901$) and between the two groups without representation control (rc-nrc and nrc-nrc, $t\ (170.52) = 2.07$, $p = .168$).

Figure 6. Results of Experiment 2 for the Transfer Phase. a) Time on Task in Seconds, b) Proportion Correct. Error bars represent the standard error of the mean. rc: representation control; nrc: no representation control.

Proportion correct during practicing and reproduction.

As shown in Figure 4b) and 5b), groups with representation control performed more accurately than groups without representation control in mismatch trials during practicing and testing. Additionally, the group that changed from practicing with representation control to testing without representation control (rc-nrc) declined in performance in the testing phase.

A GLME analysis on proportion correct also revealed a significant three-way interaction of matching, condition, and phase, $\chi^2(3) = 13.32$, $p = .004$, whereby not all lower-level interactions and main effects reached significance (see Tab. 2 and Fig. 4b and Fig. 5b). We calculated the same contrasts as for time on task, starting with those for match trials and followed by those for mismatch trials.

In match trials, neither for the practice phase nor for the reproduction task in the testing phase were differences in proportion correct found between the groups, all $|z| \leq 1.52$, $p \geq .424$. With regard to learning, only the two groups for which the availability of representation control did not change between both phases improved from practicing to reproduction in match trials (for rc-rc: $z = -2.48$, $p = .013$, for nrc-nrc: $z = -2.43$, $p = .015$) whereas in the other two groups proportion correct in match trails did not improve from practicing to repoduction (all $|z| \leq 1.25$, $p \geq .212$).

For mismatch trials during practicing, groups with representation control (rc-rc and rc-nrc) performed more accurately than groups without representation control (nrc-rc and nrc-nrc), $z = 4.80$, $p < .001$, with no differences between the two groups with representation control (rc-rc and rc-nrc), $z = 0.74$, $p = .881$, and between the two groups without representation control (nrc-rc and nrc-nrc), *z* = 0.62, *p* = .926. In the testing phase, groups with representation control (rc-rc and nrc-rc) performed more accurately than groups without representation control (rc-nrc and nrc-nrc), *z* = 4.07, *p* < .001. The two groups with representation control during testing (rc-rc and nrc-rc) did not differ, *z* = 0.89, *p* = .809; whereas the two groups without representation control during testing (nrc-nrc and rc-nrc) differed, *z* = -3.10, *p* = .010.

The proportion correct for mismatch trials increased from practicing to testing for both groups who practiced without representation control (for nrc-rc: *z* = -3.29, *p* = .001; for nrc-nrc: *z* = -2.74, *p* = .006). In contrast, the group with representation control in both phases showed no improvement, *z* = -1.73, *p* = .083. Most strikingly, however, the group that changed from practicing with representation control to testing without representation control (rc-nrc) even declined in performance, *z* = 2.87, *p* = .004.

Insert Table 2 here

Proportion correct during transfer.

As shown in Figure 6b), groups with representation control during the transfer task responded more accurately than the groups without representation control during the transfer task of the testing phase. A GLME analysis on proportion correct also revealed a significant interaction of matching and condition, $\chi^2(3) = 11.18$, *p* = .011, with both main effects also reaching significance ($\chi^2(1) = 15.20$, *p* < .001 for matching and $\chi^2(3) = 25.70$, *p* < .001 for condition; see also Fig. 6b). In match trials, the groups with representation control during the transfer task responded more accurately than the groups without representation control during the testing phase (rc-rc / nrc-rc vs. rc-nrc / nrc-nrc), *z* = 2.18, *p* = .029, with no differences between the two groups with representation control (rc-rc and nrc-rc, *z* = 2.24, *p* = .107) and between the two groups without representation control (rc-nrc and nrc-nrc, *z* = 0.92, *p* = .787).

In mismatch trials, there was also a difference in the proportion correct between groups with and without representation control during the testing phase (rc-rc / nrc-rc vs. rc-nrc / nrc-nrc), $z = 6.14$, $p < .001$, with no differences between the two groups with representation control during testing (rc-rc and nrc-rc), $z = -0.26$, $p = .994$, and between the two groups without representation control during testing (rc-nrc and nrc-nrc), $z = 1.51$, $p = 0.420$.

Use of interactive features.

The analysis of the reorganizing behavior in all three phases revealed the same pattern of results (see Fig. 7): If representation control was available, participants reorganized the visualizations more often in mismatch trials than in match trials. Neither condition (rc-rc, rc-nrc, nrc-rc) nor the interaction of matching and condition had an influence on the reorganizing behavior. The results are shown in Table 3.

Figure 7. Proportion of Trials that were Reorganized a) in the Practice Phase, b) in the Reproduction Phase, c) in the Transfer Phase of Experiment 2. Error bars represent the standard error of the mean. rc: representation control; nrc: no representation control.

Regarding the information reduction behavior, differences were visible only in the transfer part. The participants who had practiced without representation control (nrc-rc) reduced information in the visualization less often than participants who had practiced with representation control. The analysis of the information reduction behavior during practicing showed that neither matching ($\chi^2(1) = 1.50$, $p = .220$) nor the condition ($\chi^2(1) = 0.06$, $p = .810$), nor their interaction ($\chi^2(1) = 0.48$, $p = .489$) had an influence on the reductions. The same applied to the reproduction part of the testing phase. Neither matching ($\chi^2(1) = 0.30$, $p = .586$) nor condition ($\chi^2(1) = 0.41$, $p = .520$) had an influence on the information reduction behavior. Also, the interaction of matching and condition did not reach significance, $\chi^2(1) =$

3.05, $p = .081$. For the transfer part of the testing phase, however, the information reduction behavior differed between conditions, $\chi^2(1) = 11.28, p = .001$. The participants who had practiced without representation control (nrc-rc) reduced information in the visualization less often during transfer than those participants who had practiced with representation control. Neither matching, $\chi^2(1) = 0.02, p = .895$ nor the interaction of matching and condition, $\chi^2(1) = .92, p = .337$ had an influence on the reduction behavior in the transfer tasks.

Figure 8. Proportion of Trials in Which Information was Reduced a) in the Practice Phase, b) in the Reproduction Phase, c) in the Transfer Phase of Experiment 2. Error bars represent the standard error of the mean. rc: representation control; nrc: no representation control.

Insert Table 3 here

Discussion

The second experiment extended our findings of Experiment 1 regarding the *effects with* representation control in the practice phase and the *effects of* representation control on performance in the testing phase to a near transfer task and a longer time span between the two phases. In agreement with our hypothesis and the results of Experiment 1, representation control was heavily used for the mismatch trials, whereas it was used to a lower degree for the match trials. Further, in line with our previous results, the participants who had representation control available in mismatch trials outperformed those participants who did not have representation control available in terms of the proportion correct as well as the time on task. This was true for the practice phase as well as for the reproduction and transfer parts of the testing phase and supports the view that representation control fosters immediate problem solving.

With regard to the *effects of* representation control on knowledge acquisition about the underlying task structure, Experiment 2 expands our findings from Experiment 1. Depending on whether the participants solved the tasks in the preceding practice phase with or without the aid of representation control, the groups with representation control in the testing phase performed differently in the mismatch trials of the reproduction tasks. More specifically, learners who had representation control available in the practice phase responded more slowly and with a lower proportion correct in the reproduction task than users who did not have representation control available during practice. This result suggests that users who used representation control during practicing did not acquire knowledge about the underlying task structure to a sufficient degree and therefore were not able to stay on the same level of performance in the reproduction task.

The results of the other two groups – the ones with representation control in the testing phase – did not differ from each other in the reproduction task. The participants who first practiced the tasks without representation control and then had representation control available in the testing phase responded just as fast and correctly as the participants who used representation control in both phases. This finding indicates that the negative effect of representation control on the performance in a testing phase without representation control is not simply a compatibility effect between practicing and testing conditions. If it had been a compatibility effect, the two groups with similar conditions during practicing and testing (either representation control available or not available in both phases) should have outperformed the two groups with a change of condition (from representation control during practicing to no representation control during testing or vice versa), which was not the case in the present study.

A further goal of this experiment was to extend our knowledge about the generalization of the effect to a near transfer task with a differing surface organization. We showed that the results in a reproduction task do not directly generalize to a near transfer task. More specifically, in contrast to the findings from the reproduction task, the performance of the group with representation control only in the practice phase and the group without representation control in both phases was largely similar. That means, in line with research on transfer of problem-solving skills (e.g. Catrambone & Holyoak, 1989), the group without representation control in both phases failed to transfer their skills to problems with a diverging spatially organization. However, the interaction behavior of the two groups with representation control in the testing phase differed: The participants who had representation control available only in the testing phase reduced information density less often in the transfer task than those participants who could already use representation control in the practice phase. This indicates that the participants who had representation control only available in the testing phase acquired knowledge about the underlying structure of the task to a sufficient degree and therefore did not need to reduce information density very often in order to be able to solve the problem correctly in the testing phase.

Experiment 3

One possible explanation for the findings of Experiments 1 and 2 is that although the participants were allowed to adjust the visualizations, the adjusting procedure might not have served as a model for successful task solution because it did not depict the sequential steps of the task solution systematically. Additionally, planning and executing epistemic actions may also have required a substantial amount of cognitive resources, thus preventing the participants from elaborating the underlying task structure sufficiently. In Experiment 3, we therefore used different types of representation control in the practice phase of the experiment, varying in both automation and explicitness of the required solution steps. The purpose of this experiment was to investigate whether such a systematic presentation of sequential steps prepares the users for situations in which representation control is no longer available. Based on Salomon´s model (Salomon, 1974, 1994), Experiment 3 compared three types of representation control, namely, an active representation control condition (identical to the representation control condition of Experiment 1 and to the rc-nrc condition of Experiment 2), a stepwise modeling condition, and a short-circuit condition. As in Experiment 1, we explored the time on task as well as the proportion correct as proxies for task performance in both phases. Furthermore, we also analyzed how often our participants used the interactive features in the practice phase.

For the practice phase, we hypothesized that the performance in the short-circuit condition should be superior to the performance in the modeling condition, which in return should be superior to the performance in the active representation control condition. For the testing phase, we hypothesized that the modeling condition relieves the participants of the requirements of planning and executing, thus allowing them to better observe, memorize, and thereby internalize the respective processing steps. This, in turn, should lead to an enhanced task performance of the modeling condition in the testing phase. In contrast, the benefit of observation should be absent in the short-circuit condition in which the participants only see the final state of the transformation without the intermediate steps.

Methods

Participants.

The final sample consisted of 160 participants (mean age: 22.44 years, range 18-30 years, 119 females) recruited from the local participant pool of our research center. They were randomly assigned to one of the four conditions. The data from one participant was excluded due to technical problems. The experimental procedure was approved by the ethics committee of our research center. All participants gave informed consent prior to testing.

Apparatus and materials.

Apparatus and materials were the same as in Experiment 1 with the following exceptions. There were three conditions in which the participants had different types of representation control in the practice but not in the testing phase of the experiment. We repeated the *active representation control condition* of Experiment 1 in which the participants were able to reorganize the maps spatially as well as to reduce information density with the displayed interaction menu.

In the *modeling condition*, the interaction menu was grayed out and its function was replaced by an ‘adjust’ button. When the participants clicked on this button, the two irrelevant information layers were removed stepwise from the maps. In mismatch trials, the maps were additionally reorganized spatially, so that the remaining relevant information was depicted in one map rather than being spread between the two maps. Hence, the resulting representation always contained the remaining task-relevant information depicted in one map. Importantly, all transformations were executed and depicted sequentially so that the participants saw them in a step-by-step manner. The total duration of the transformation was 2 seconds for match trials and 3 seconds for mismatch trials.

The *short-circuit condition* was identical to the modeling condition with the exception that the transformation processes were not visible to the participants and the resulting visualization appeared immediately after clicking onto the adjust button.

As in Experiment 1, we also included a baseline condition in which participants completed only the testing phase of the experiment without representation control.

Procedure.

The procedure was identical to that of Experiment 1. The participants in all conditions watched an instructional video that explained the task and the condition-specific interactive features of the visualizations before the practice phase started.

Analysis.

Data preparation and the analysis procedure were identical to Experiment 1. Time on task was also measured exactly the same. Thus, time on task is the duration from the onset of the presentation of the visualization until the confirmation of the response by the user through a click on the proceed button, including all transformation times. Again, we excluded trials with a time on task deviating more than four standard deviations from the mean time on task (0.79% of all trials). Additionally, we conducted a GLME analysis for the two conditions that used the adjust button in the practice phase (adjust condition and step-by-step condition). We included matching and condition as fixed effects in the model as well as random intercepts and random slopes for matching per participant and random intercepts for each visualization. In the analysis of the reduction of information density, we excluded one trial in which the participant eliminated the irrelevant information only partially.

Results

Practice Phase.

Time on task.

As in Experiment 1, the LME analysis of the log-transformed time on task revealed a significant interaction of matching and condition, $\chi^2(2) = 11.65$, $p = .003$, indicating that the influence of condition differed between match and mismatch trials (see Fig. 9a). For mismatch trials, planned *t*-tests with Tukey adjustments for multiple comparisons indicated that the time on task in the active representation control condition was longer than the time on task in the short-circuit condition, $t(116.90) = 2.79$, $p = 0.017$. However, the numerical difference between the time on task in the active representation control condition and the modeling condition did not reach significance, $t(117.01) = 2.02$, $p = 0.112$. Also, the time on task for the short-circuit condition and the modeling condition did not differ significantly from each other, $t(117.05) = -0.77$, $p = 0.723$. For match trials, the time on task in the active representation control condition was longer than the time on task in the short-circuit condition, *t*(117.04) = 2.52, *p* = 0.035, as well as the time on task in the modeling condition, *t*(117.01) = 3.40, *p* = 0.003, whereas the short-circuit condition and the modeling condition did not differ from each other, *t*(116.88) = 0.88, *p* = 0.654. Furthermore, the LME analysis revealed a significant main effect of matching, $\chi^2(1) = 46.77$, $p < .001$, as well as a significant main effect of condition, $\chi^2(2) = 10.07$, $p = .007$.

Figure 9. Results of the Practice Phase of Experiment 3. a) Time on Task, b) Proportion Correct. Error bars represent the standard error of the mean.

Proportion Correct.

A GLME analysis on the proportion correct revealed that neither the interaction, $\chi^2(2) = 1.20$, $p = .548$, nor the main effects of condition, $\chi^2(2) = 0.55$, $p = .758$, nor of matching, $\chi^2(1) = 0.94$, $p = .332$, reached significance (see Fig. 9b).

Use of interactive features.

In the active representation control condition, a GLME analysis revealed a significant main effect of matching on reorganizing, $\chi^2(1) = 55.37$, $p < .001$. Consistent with the results of Experiment 1 and Experiment 2, the participants reorganized the visualization in 91 % (*SD* = 28 %) of the mismatch trials, but only in 8% (*SD* = 28 %) of the match trials. Also, consistent with the results of the two other experiments, our participants reduced information density equally often in mismatch, (*M* = 73 %, *SD* = 44 %), and match trials, (*M* = 74 %, *SD* = 44 %), $\chi^2(1) = 0.21$, $p = .646$. In the short-circuit condition and the modeling condition, a GLME analysis revealed that the participants used the adjust button more often in mismatch than in match trials, $\chi^2(1) = 7.01$, $p = .008$ (see Fig. 10). Neither the main effect of condition,

$\chi^2(1) = 0.19$, $p = .661$, nor the interaction between condition and matching, ($\chi^2(1) = 1.57$, $p = .210$), reached significance.

Figure 10. Proportion of Trials That Were adjusted in the Practice Phase of Experiment 3. Error bars represent the standard error of the mean.

Testing Phase.

For the analysis of the testing phase, additional data of one participant were excluded. All her responses in the mismatch trials for the testing phase were incorrect (i.e. no plausible time on task data), suggesting that she failed to comply with the instructions in the testing phase.

Time on task.

A LME analysis on the log-transformed time on task revealed an interaction of matching and condition, $\chi^2(3) = 7.87$, $p = .049$. Furthermore, the main effects of matching, $\chi^2(1) = 64.74$, $p < .001$, as well as condition, $\chi^2(3) = 8.81$, $p = .032$, reached significance (see Fig. 11a). Pairwise comparisons with Tukey adjustments for multiple comparisons revealed a significant difference for the time on task of the baseline without practice and the modeling condition in match trials, $z = 3.70$ $p = 0.001$. No other pairwise comparisons within match as well as within mismatch trials reached significance (all $|z| \leq 2.03$, all $p > .179$).

Figure 11. Results of the Testing Phase of Experiment 3. a) Time on Task, b) Proportion Correct. Error bars represent the standard error of the mean.

Proportion correct.

A GLME revealed that only matching had an influence on the proportion correct, $\chi^2(1) = 12.44$, $p < .001$, with more errors in mismatch than in the match trials (see Fig. 11b).

Neither the main effect of condition, $\chi^2(3) = 2.88$, $p = .410$, nor the interaction of matching and condition, $\chi^2(3) = 4.93$, $p = .177$, reached significance.

Discussion

The third experiment investigated how the availability of different types of representation control in a practice phase affects the performance in a testing phase without these interactive features. The different types of representation control either required active planning and execution of task appropriate reorganization of visualizations (active representation control), modeled the reorganization in a step-by-step demonstration (modeling), or reorganized it instantly without presenting intermediate steps (short-circuit).

In line with our hypotheses for the practice phase, we observed a shorter time on task in the modeling condition that demonstrated the reorganization of the visualizations in a systematic way rather than leaving this task to the participants (active representation control condition). This was especially apparent in the trials in which the initial organization of the visualizations matched the task demands. The participants in both automated conditions (i.e. modeling condition and short-circuit condition) responded faster than the participants in the active representation control condition. We argue that this stems from the additional costs from planning and executing the transformations in the active representation control condition.

Regarding our hypotheses for the *effects of* representation control in the testing phase, the results were mixed. In line with our expectations, the learners in the modeling condition had shorter times on task than those in the untrained baseline condition for match items, while this benefit was not present for the active representation control condition as well as the short-circuit condition. This is consistent with the research on problem-solving skills in which worked-out problems resulted in equal or higher performance than practice with conventional problems (Catrambone & Holyoak, 1989; Paas, 1992). However, contrary to our expectations, there were no differences between the conditions in mismatch trials. Neither the participants in the active representation control condition, the modeling condition, nor the short-circuit condition benefited from solving the mismatch trials in the practice phase of the experiment. Instead, they performed at a level similar to the untrained baseline group in the testing phase. In sum, these results partly support Salomon's (Salomon, 1974, 1990, 1994) view that systematic demonstration of epistemic activities may help learners to observe, memorize, and thereby internalize the respective processing steps. At the same time, the pattern of results suggests that the complexity of the sequence of steps mediates the effectiveness of such a demonstration of epistemic activities. We will further elaborate on this issue in the following general discussion section.

General Discussion

In the present three experiments, we investigated the *effects with* and the *effects of* the availability of representation control on problem solving in an information extraction task. We considered representation control (i.e. the intentional reorganizing of an information display according to task requirements) to be a typical example of epistemic activities that are performed to offload cognitive processes into the environment. Therefore, we were interested in whether participants acquire knowledge about the underlying task structure or procedural knowledge about the representation control itself.

To test this, we varied the availability of representation control in two experimental phases. In Experiment 1 and Experiment 3, our participants first practiced the problems with the possibility of using representation control before representation control was no longer available in the testing phase of the experiments. In Experiment 2, the availability of representation control was independently varied for the practice and the testing phase of the experiment. According to previous research on cognitive offloading (e.g. Moritz et al., 2018; Carlson et al., 2007; Chu & Kita, 2011; Gilbert, 2015; Goldin-Meadow et al., 2001; Risko et al., 2014), we hypothesized that representation control is useful for immediate task solution (i.e., *effects with* representation control), especially in trials in which the task focus and the spatial organization of the visualizations do not match. This prediction was confirmed in Experiment 1 and Experiment 2 as the participants with representation control outperformed those without representation control in the practice phase, especially with problems with a spatially mismatching initial display. This pattern of results was visible in the time on task within the mismatch trials as well as the proportion correct of Experiment 1. In Experiment 2, it was visible in the time on task for both match and mismatch trials as well as in the proportion correct of the mismatch trials. Similarly, in Experiment 3, the benefit of representation control regarding the time on task was larger for the more automated types of control.

However, beyond the immediate effects with representation control, it is important to consider the long-term effects of representation control with regard to knowledge about the underlying problems (*effects of* representation control; i.e. the skill to solve these problems without interactively modifying external representations). Former empirical results allowed for the prediction of a positive (e.g. Salomon, 1979) as well as a negative influence (Bjork & Bjork, 2011) of representation control on knowledge acquisition with regard to the underlying problem structure. To test this, we eliminated the availability of representation control in the testing phases of our experiments. In Experiment 1, we observed that participants in the representation control condition fell back to the level of an untrained baseline condition for tasks in which they had relied on representation control for the task solution in the practice phase. In Experiment 2, we observed that the participants who had to go without representation control in the reproduction task of the testing phase after using it in the practice phase performed inferior (i.e. slower and less accurate) to the participants who had to go without representation control throughout the whole experiment (i.e. also in the practice phase) when the task did not match the spatial organization of the visualization. These findings suggest that the participants did not acquire knowledge about the underlying structure of the task to a sufficient degree if they were able to reorganize the visualization according to the task demands in the practice phase of the experiment. To the contrary, in Experiment 2 we observed that the participants who had representation control available in the testing phase but not in the practice phase and therefore relied on their mental resources to solve the task in the practice phase, performed equally well in the testing phase as those who always had representation control available. Considering the pattern of results from a temporal perspective, it means that even though the practice phase lasted no more than half an hour, it influenced the performance in the reproduction task on the following day.

In Experiment 2, we also investigated the effect of representation control on the performance in a near transfer task. While the availability of representation control in the practice phase had no direct effect on the participants' performance in the transfer task without representation control, they used the opportunity to reduce information in the visualization to a different degree. This again indicates that the participants who had practiced the task without representation control were better able to acquire knowledge about the underlying structure of the task to a sufficient degree.

Two possible explanations for the result that the condition that had to go without representation control in the testing phase after having used it in the practice phase were tested in Experiment 3, namely, that planning and executing the reorganization of the visualization according to task demands might have been too unsystematic or too cognitively demanding, or both. To test this, we compared three different conditions: an active representation control condition in which participants had to actively plan and execute each step of reorganizing the visualization, a modeling condition in which all necessary steps of reorganizing were visibly executed by the software, and a short-circuit condition in which the visualization switched automatically to the optimal presentation format without showing the intermediate steps. The three conditions can be considered different forms of representation control as they all allow the learner to adjust the format of the representation to the requirements of the task at hand. However, both the modeling condition and the short-circuit condition constrain the interactive options that the participants can choose from. This reflects the fact that representation control is not an all-or-nothing issue but should be considered a dimension that allows for options to modify the spatial organization of a given visualization according to task demands to a different degree. In particular, while the active representation control condition gives the learner control over the individual steps of the task procedure, both the modeling condition and the short-circuit condition still serve for offloading cognitive transformations into visual representations. However, they aggregate the individual steps into a multistep process of restructuring the visualization, which is elicited by the learner by means of a single decision. Accordingly, we observed a shorter time on task in the modeling condition (which reduced the learners' requirements for active control while still visibly demonstrating the necessary procedural steps) than in an untrained baseline condition, but only for those tasks in which the visualization spatially matched the task demands.

Theoretical Implications

Overall, our findings highlight the important distinction between task performance and knowledge acquisition when working with representation control. In line with previous accounts of cognitive offloading and epistemic action (e.g. Moritz et al., 2018; Carlson et al., 2007; Chu & Kita, 2011; Gilbert, 2015; Goldin-Meadow et al., 2001; Risko et al., 2014), we demonstrated that representation control is efficient in increasing immediate task performance. However, we could not find evidence that the availability of representation control helped the learners to acquire some knowledge about the underlying task structure. This is evident from the pattern of subsequent task performance without representation control, irrelevant to whether the time duration that separated the two phases was 20 minutes or a whole day.

Yet, according to Experiment 3, knowledge acquisition as indicated by subsequent task performance without representation control relative to an untrained baseline condition resulted only when the following three criteria were met: First, the representation control had to be automated to a high degree, thereby relieving the learners from planning and execution of epistemic actions. Second, the representation control had to demonstrate the task appropriate reorganization of the visualization in a systematic and stepwise manner, thus allowing the learners to subsequently observe the relevant transition states. Third, the sequence of steps had to be of low complexity as was the case for the match but not for the mismatch trials.

To sum up, the pattern of results reveals an inherent trade-off between task performance and procedural learning when solving problems with representation control. On the one hand, task performance benefited most from representation control under highly complex task conditions in which the organization of the information display and the task demands largely diverged. In fact, the participants of all three studies seem to have been well aware of the interplay between task structure and representation control by appropriately using the options of reorganizing the visualization predominantly in mismatch trials.

On the other hand, procedural learning benefited from representation control only under very specific circumstances. The general pattern of findings across the three experiments is in accordance with the notion of desirable difficulties, stating that easing the learning process – in the present case through cognitive offloading via representation control - bears the risk of decreased learning outcomes. Only under low complex task conditions that required just a few steps of reorganization that can be easily internalized was representation control shown to facilitate learners in subsequent task performance with no opportunity for cognitive offloading. Therefore, our findings also expand the findings of Salomon (1979) by showing that learners benefit most from explicitly modeling a task solving procedure when the task is of sufficiently low complexity (which was also the case in the studies reported by Salomon, 1979).

Practical Implications

Due to the increasing use of digital textbooks and learning apps, interactive types of visualizations have become an important type of learning material, both in schools and in higher education; however, their design and also their appropriate use in education is still under debate (Hirsh-Pasek, Zosh, Golinkoff, Gray, Robb, & Kaufman, 2015; Pimmer, Matescu, & Gröhbiel, 2016). In this context, studies of representation control of visualizations have mainly focused on their immediate effects on the acquisition of learning contents (e.g. Schwan & Riempp, 2004; Delen, Liew, & Wilson, 2014; Weng, Otanga, Weng, & Cox, 2018), which corresponds to the notion of *effects with media* in the model by Salomon and Perkins (2005). The present study extends this line of research with respect to the long-term effects of the use of representation control on procedural learning when this control feature is no longer available to the learner. We observed that the effects *with* cognitive offloading are positive in an information extraction task but that potential benefits *of* cognitive offloading on the acquisition of procedural knowledge beyond using the specific tool are severely limited. We further showed that reducing active representation control while still visually demonstrating the required procedural steps might substantially reduce the observed detrimental effects. Therefore, in line with the desirable difficulties approach, the distinction between *effects with* and *effects of* representation control may therefore serve as a model to guide the implementation of interactive features for visualizations in learning materials (Salomon & Perkins, 2005).

Interactive features can, on the one hand, facilitate answering specific questions if the goal of a visualization is to inform the learner and to provide answers to these questions. On the other hand, learners rarely do benefit from their experience with adjustable visualizations when the interactive features are no longer available. Especially developers of instructional material who intend to teach people by using visualizations should keep this distinction in mind. Interactive features - including representation control - are beneficial for accomplishing a given task, but the use of these features does not necessarily lead to learning about the underlying task structure. Such a procedural learning requires the following conditions: First, the presentation of the task solution needs to be automatic, thus relieving the participants from planning and executing the transformations. Second, the presentation of the task solution needs to be sequential (i.e. one step after another). Third, the problems need to be sufficiently easy to allow for the internalization of the underlying problem structure.

Limitations

As any other study, there are some limitations to our study that should be considered carefully before generalizing our result too broadly. The most severe limitation is that we have studied the effect of representation control on procedural learning in an incidental learning setup. Our participants were not told beforehand that they would have to solve a second set of problems in a testing phase without interactive features. Thus, it remains possible that the participants would have acquired knowledge about the underlying task structure had they been instructed to do so in an explicit learning task. Further research should investigate the *effects with* and *effects of* representation control in an explicit learning environment. Nevertheless, as most everyday activities reflect incidental rather than intended learning, our study clearly restricts the beneficial *effects of* technology to the more formal learning setups.

Another limitation of our study is the duration of the practice phase. In total, the participants had approximately 45 minutes (24 trials) to acquire knowledge about the tool as well as the underlying problem structure. A longer exposure to the problems might therefore have resulted in more positive results regarding the *effects of* representation control. In incidental learning tasks such as leisure activities, however, exposure also is rather short. This strikingly contrasts with formal learning setups that typically exhibit much longer intervals of exposure.

Conclusion

In sum, our study shows that observers are capable of picking up facilitatory strategies in using representation control during problem solving. Importantly, however, for the studied case of incidental learning, the beneficial effects stem from knowledge about how to use the representation control rather than from knowledge about the structure of the underlying problem. Our study therefore highlights the importance of considering the differentiation between the effects with and the effects of representation control for designers of interactive visualizations.

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Tables

Table 1

Results of the mixed model regression analysis on log-transformed time on task for practicing and reproduction in Experiment 2

Effect	X^2	df	*p*
Match	302.43	1	< .001
Condition	9.65	3	.02
Phase	8.82	1	.003
Match x Condition	102.32	3	< .001
Match x Phase	22.54	1	< .001
Condition x Phase	135.03	3	< .001
Match x Condition x Phase	170.13	3	< .001

Table 2

Results of the mixed model regression analysis on proportion correct for practicing and reproduction in Experiment 2

Effect	X^2	df	*p*
Match	25.54	1	< .001
Condition	8.27	3	.041
Phase	6.83	1	.009
Match x Condition	5.48	3	.140
Match x Phase	2.06	1	.151
Condition x Phase	18.92	3	< .001
Match x Condition x Phase	13.32	3	.004

Table 3

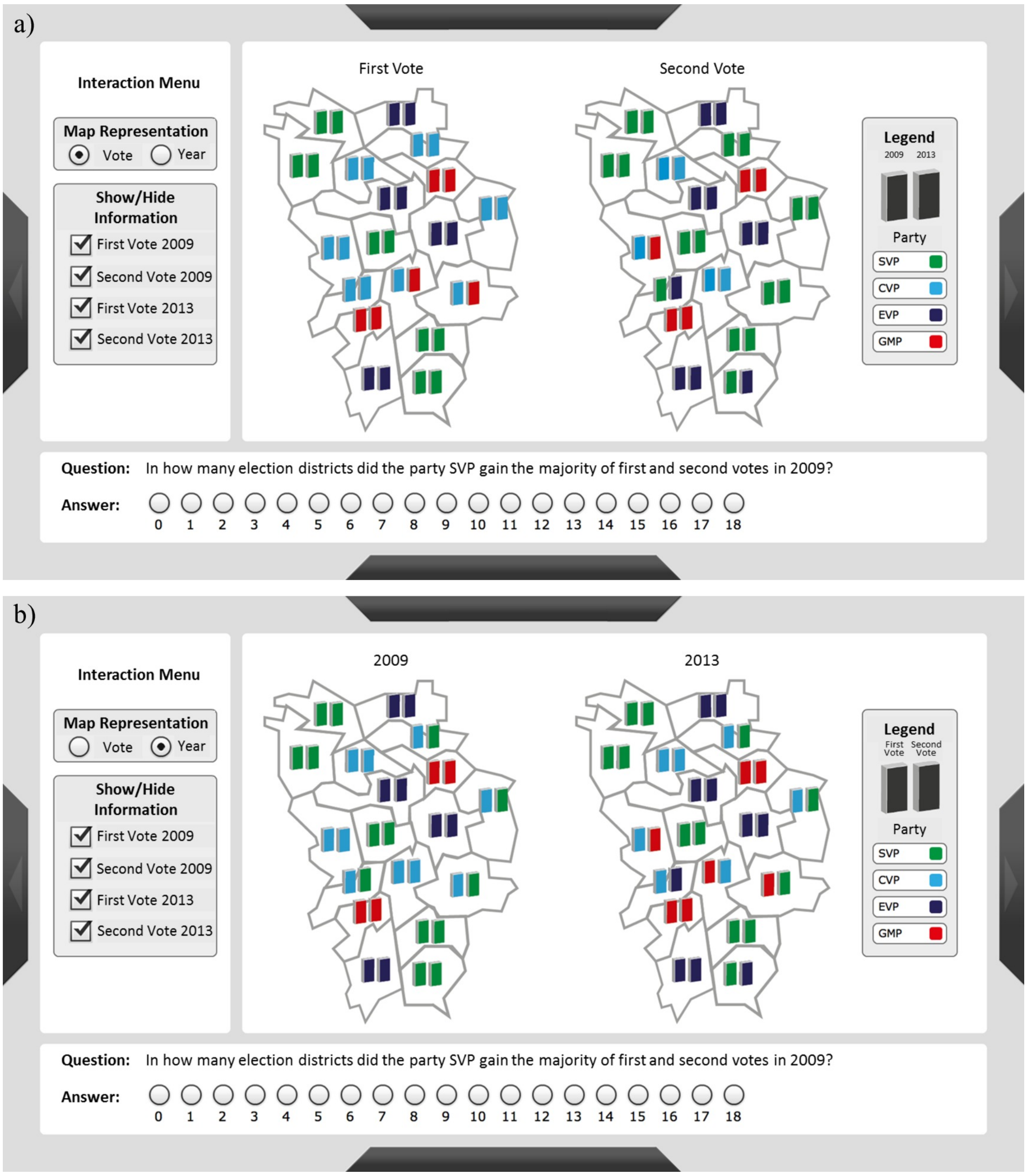
Results of the mixed model regression analysis on restructuring behavior in Experiment 2

	Practice			Reproduction			Transfer		
Effect	X^2	df	*p*	X^2	df	*p*	X^2	df	*p*
Match	110.58	1	< .001	148.83	1	< .001	102.84	1	< .001

Condition	0.36	1	.547	1.02	1	.313	0.12	1	.728
Match x Cond.	0.05	1	.817	0.46	1	.499	0.66	1	.417

Note. Cond. = Condition

Figures



a)

Map Representation: ● Vote ○ Year

Show/Hide Information
☑ First Vote 2009
☑ Second Vote 2009
☑ First Vote 2013
☑ Second Vote 2013

Question: In how many election districts did the party SVP gain the majority of first and second votes in 2009?

b)

Map Representation: ○ Vote ● Year

Show/Hide Information
☑ First Vote 2009
☑ Second Vote 2009
☑ First Vote 2013
☑ Second Vote 2013

Question: In how many election districts did the party SVP gain the majority of first and second votes in 2009?

Figure 1. Illustration of the information graphics used in all three experiments. The maps were initially organized (a) by type of vote or (b) by election period. Interactive reorganization was possible only in the conditions with representation control. Only in these conditions, the interaction menu (left) was present. See the online article for the color version of this figure.

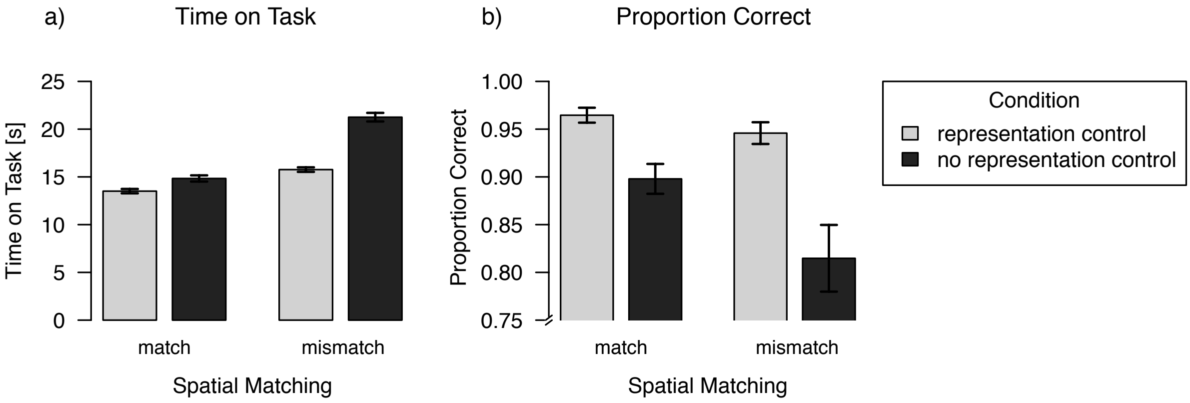


Figure 2. Results of the practice phase of Experiment 1. a) Time on task in seconds; b) proportion correct. Error bars represent the standard error of the mean.

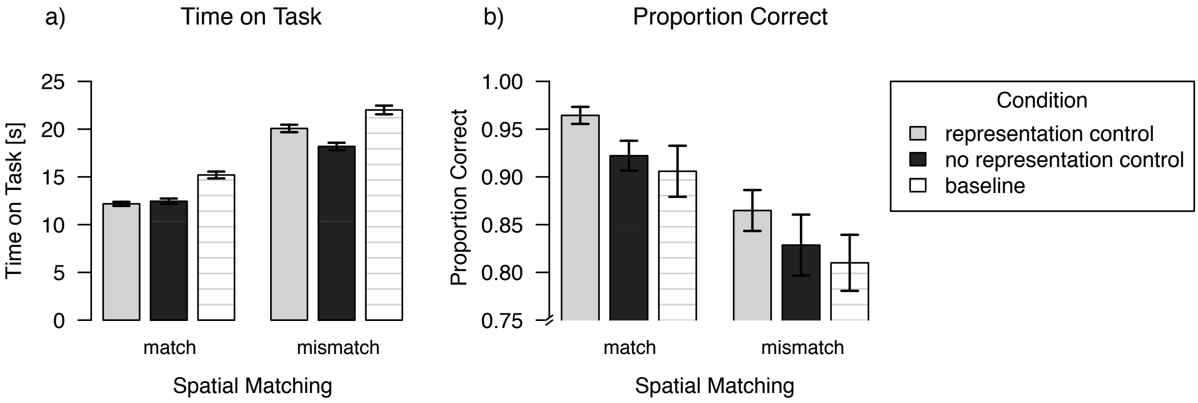


Figure 3. Results of the testing phase of Experiment 1. a) Time on task in seconds; b) proportion correct. Error bars represent the standard error of the mean.

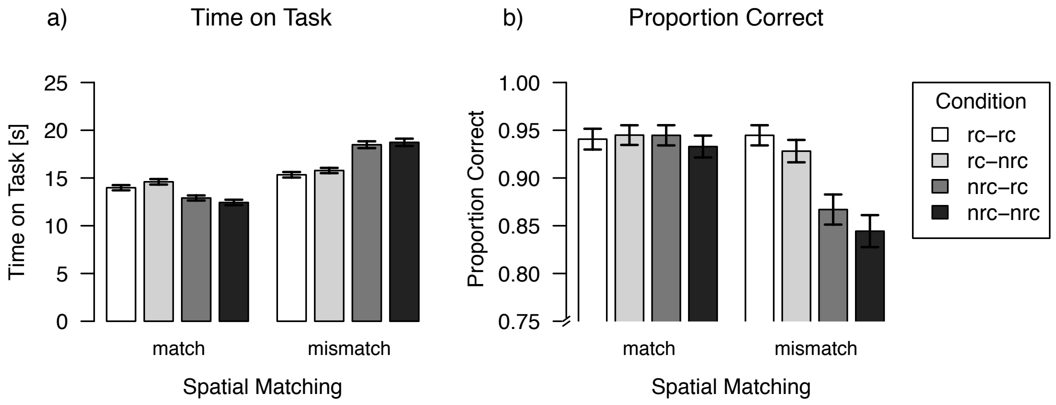


Figure 4. Results of Experiment 2 for the practice phase. a) Time on task in seconds; b) proportion correct. Error bars represent the standard error of the mean. rc = Representation control; nrc = no representation control.

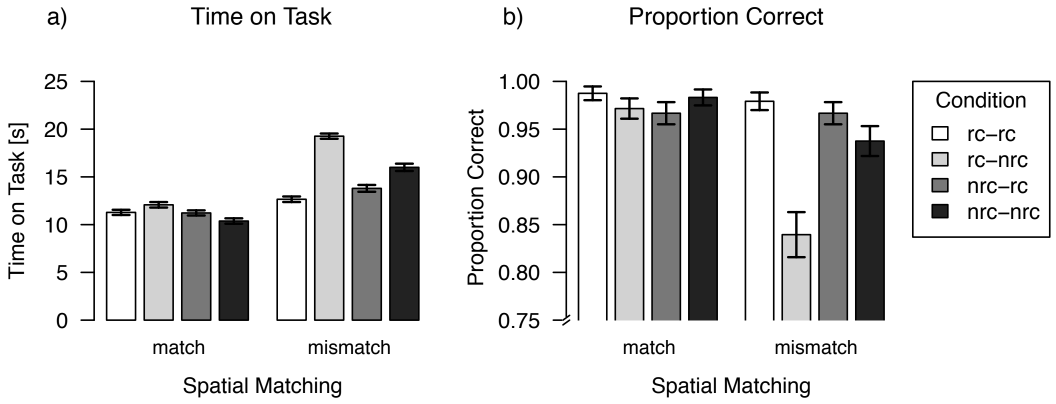


Figure 5. Results of Experiment 2 for the reproduction phase. a) Time on task in seconds; b) proportion correct. Error bars represent the standard error of the mean. rc = Representation control; nrc = no representation control.

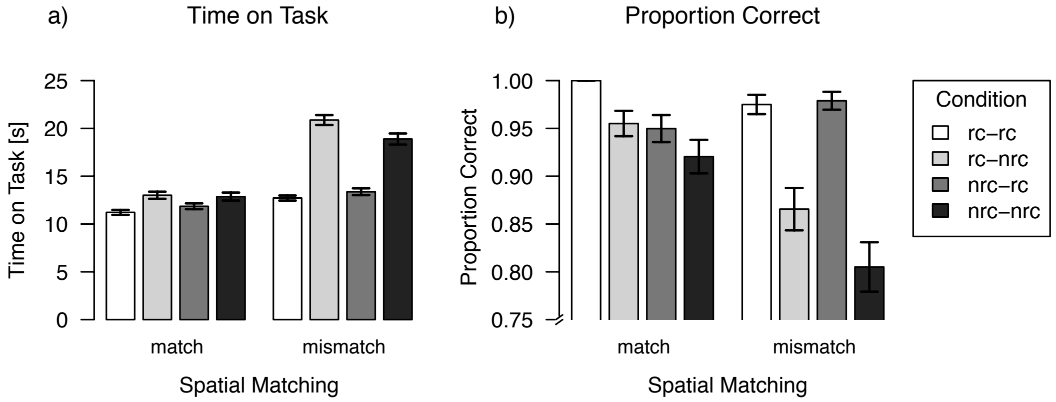


Figure 6. Results of Experiment 2 for the transfer phase. a) Time on task in seconds; b) proportion correct. Error bars represent the standard error of the mean. rc = Representation control; nrc = no representation control.

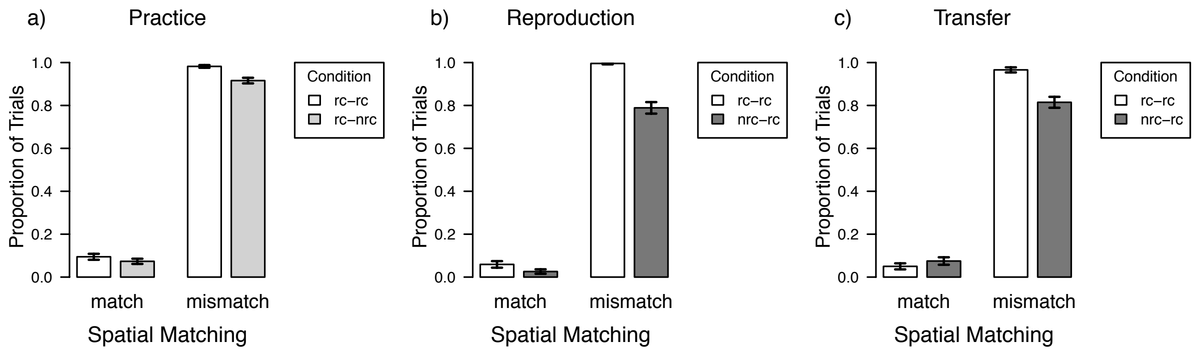


Figure 7. Proportion of trials that were reorganized a) in the practice phase, b) in the reproduction phase, c) in the transfer phase of Experiment 2. Error bars represent the standard error of the mean. rc = Representation control; nrc = no representation control.

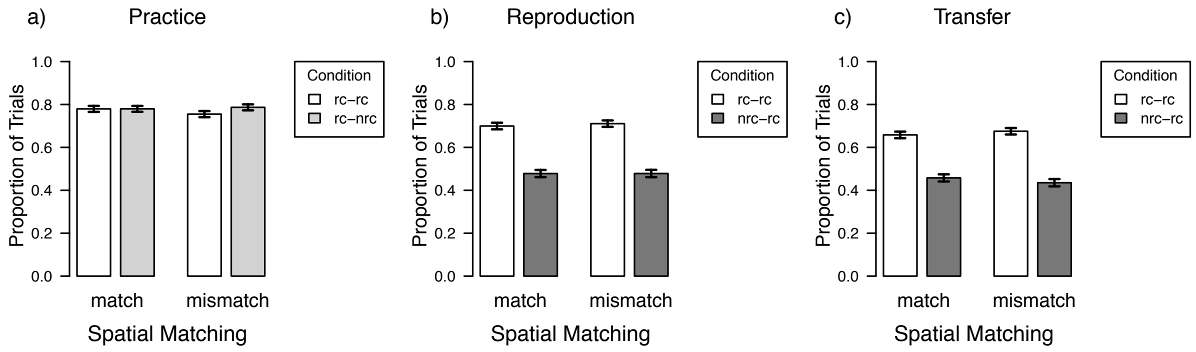


Figure 8. Proportion of trials in which information was reduced a) in the practice phase, b) in the

reproduction phase, c) in the transfer phase of Experiment 2. Error bars represent the standard error of the mean. rc = Representation control; nrc = no representation control.

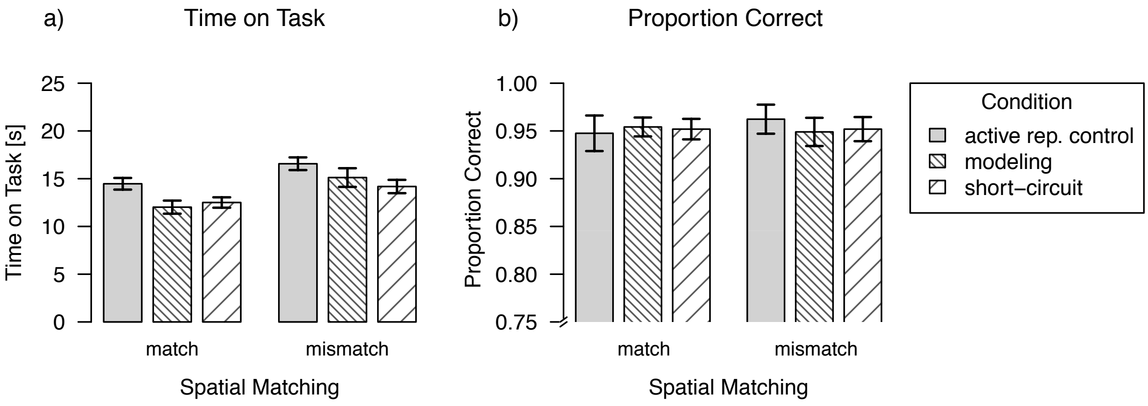


Figure 9. Results of the practice phase of Experiment 3. a) Time on task; a) proportion correct. Error bars represent the standard error of the mean.

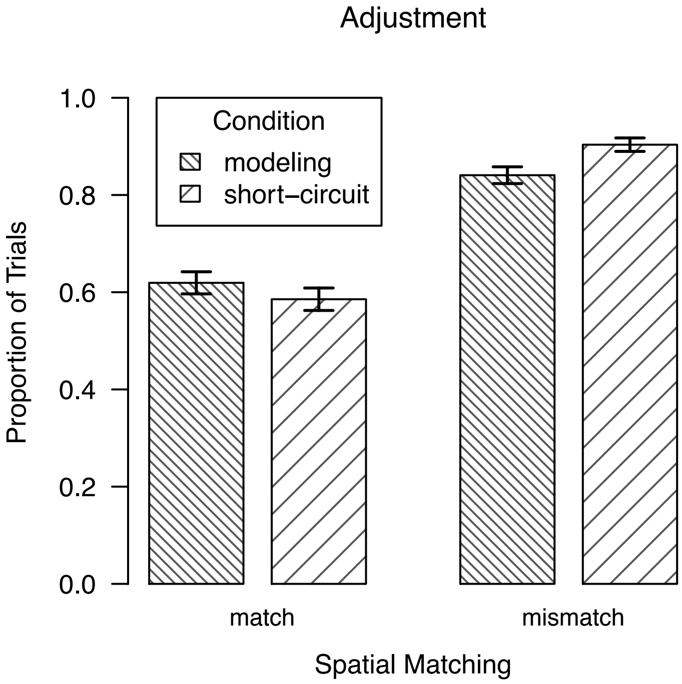


Figure 10. Proportion of trials that were adjusted in the practice phase of Experiment 3. Error bars represent the standard error of the mean.

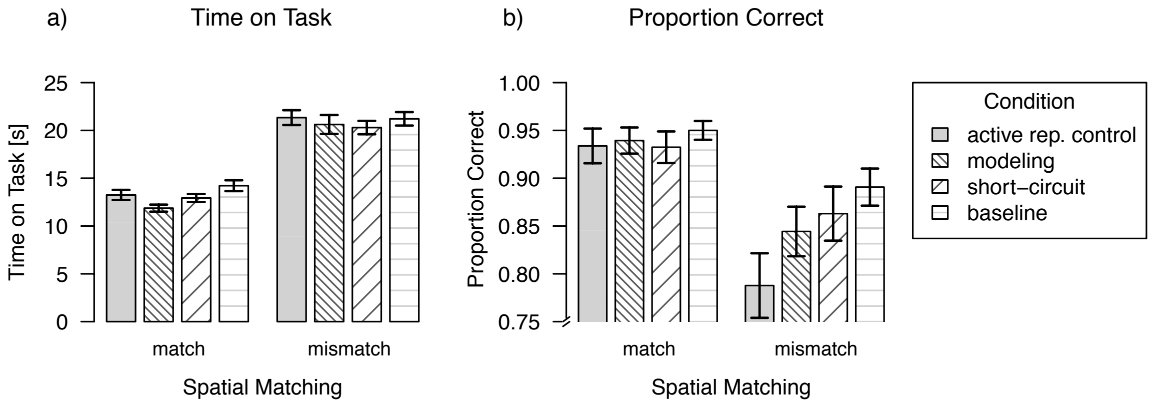


Figure 11. Results of the testing phase of Experiment 3. a) Time on task; b) proportion correct. Error bars represent the standard error of the mean.

Appendix D

Declaration according to § 5 Abs. 2 No. 8 of the PhD regulations
of the Faculty of Science

- Collaborative Publications -

Erklärung nach § 5 Abs. 2 Nr. 8 der Promotionsordnung der Math.-Nat. Fakultät
-Anteil an gemeinschaftlichen Veröffentlichungen-
Nur bei kumulativer Dissertation erforderlich!

Declaration according to § 5 Abs. 2 No. 8 of the PhD regulations of the Faculty of Science
-Collaborative Publications-
For Cumulative Theses Only!

Last Name, First Name: Moritz, Julia

List of Publications

1. Moritz, J., Meyerhoff, H. S., & Schwan, S. (in preparation). Representation control in a goal-free task: The use of reorganization and reduction in an information extraction task with infographics.
2. Moritz, J., Meyerhoff, H. S., Meyer-Dernbecher, C., & Schwan, S. (2018). Representation control increases task efficiency in complex graphical representations. *PLoS ONE*, *13*(4), 1–14. https://doi.org/10.1371/journal.pone.0196420
3. Moritz, J., Meyerhoff, H. S., & Schwan, S. (2019). Control Over Spatial Representation Format Enhances Information Extraction but Prevents Long-Term Learning. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000364

Nr.	**Accepted publication yes/no**	**List of authors**	Position of candidate in list of authors	Scientific ideas by the candidate (%)	Data generation by the candidate (%)	Analysis and Interpretation by the candidate (%)	Paper writing done by the candidate (%)
1	No	• Moritz, Julia • Meyerhoff, Hauke S. • Schwan, Stephan	1	90 %	100 %	85 %	100 %
2	Yes	• Moritz, Julia • Meyerhoff, Hauke S. • Meyer-Dernbecher, Claudia • Schwan, Stephan	1	50 %	0 %	80 %	80 %
3	Yes	• Moritz, Julia • Meyerhoff, Hauke S. • Schwan, Stephan	1	80 %	100 %	80 %	80 %

I confirm that the above-stated is correct.

Date, Signature of the candidate

I/We certify that the above-stated is correct.

Date, Signature of the doctoral committee or at least of one of the supervisors