

Information Reduction as Item-general Strategy Change

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Abstract

Practice not only affects *how* but also *which* information is processed. Past research on Information Reduction (Haider & Frensch, 1996) has underscored the importance of the latter aspect for cognitive skill acquisition. Information Reduction applies in situations in which tasks contain both relevant and irrelevant information, and denotes a change from a strategy involving processing all elements of a task to a processing-relevant-elements-only strategy. On the one hand, it has been repeatedly observed in a broad range of contexts (e.g., human-machine interaction, educational and sports psychology) that people tend to ignore irrelevant information after repeated exposure. On the other hand, both from the perspective of theories on skill acquisition and for practical concerns, it is not sufficiently understood how Information Reduction takes place and which factors foster or impede it. In the research presented here, participants had the task to verify whether or not alphanumeric strings followed the alphabetical order. These strings were a compound of two parts, one of which was always correct and thus effectively irrelevant. As the different strings were repeated at different rates per practice block, it could be tested whether people learn to ignore irrelevant aspects of a task string by string or rather once and for all strings. Information Reduction was item-general rather than item-specific. The data are inconsistent with the view that strategy change in general, and Information Reduction in particular, is exclusively based on item-specific data-driven learning processes, bare of the involvement of a voluntary decision. Rather, RTs, fixations, and transfer errors indicated that strategy change entails top-down modulation.

Keywords: Information Reduction, skill acquisition, strategy change, voluntary control

Zusammenfassung

Übung beeinflusst nicht nur *wie* sondern auch *welche* Information verarbeitet wird. Die bisherige Forschung zur Informationsreduktion (Haider & Frensch, 1996) hat die Wichtigkeit des letzteren Aspektes für den kognitiven Fertigkeitserwerb herausgearbeitet. Informationsreduktion tritt in Situationen auf, in denen Aufgaben sowohl relevante als auch irrelevante Information enthalten. Informationsreduktion stellt einen Strategiewechsel dar, bei dem ein Übergang von einer Strategie, die das Prozessieren aller Elemente einer Aufgabe beinhaltet, hin zu einer Strategie, bei der nur die relevanten Elemente prozessiert werden, stattfindet. Einerseits wurde in vielen Kontexten (z.B. Psychologie der Mensch-Maschine Interaktion, Pädagogische-, und Sport-Psychologie) beobachtet, dass Menschen dazu neigen, irrelevante Information nach mehrfacher Darbietung zu ignorieren. Andererseits ist sowohl hinsichtlich der theoretischen Auseinandersetzung mit Strategiewechsel im kognitiven Fertigkeitserwerb, als auch aus praktischer Sicht nicht genügend geklärt, wie Informationsreduktion stattfindet und welche Faktoren fördernd bzw. hemmend wirken. In der hier zusammengefassten Forschung, hatten Probandinnen und Probanden die Aufgabe zu prüfen, ob alphanumerische Zeichenketten dem Alphabet folgen oder nicht. Die Zeichenketten bestanden aus zwei Teilen. Einer der beiden Teile war immer korrekt und daher letztlich irrelevant. Da verschiedene Zeichenketten unterschiedlich oft pro Übungsblock präsentiert wurden, konnte ermittelt werden, ob Informationsreduktion Item-spezifisch oder Item-generell stattfindet. Die Frage ist also, ob die Versuchspersonen den irrelevanten Teil für jede Zeichenkette einzeln zu ignorieren lernen, oder aber die Fertigkeit zum Ignorieren des irrelevanten Teiles auf einmal für alle Zeichenketten erwerben. Letzteres traf zu, Informationsreduktion fand Item-generell statt. Die Befunde sind inkonsistent mit der Annahme dass Strategiewechsel im Allgemeinen und Informationsreduktion im Besonderen, ausschließlich durch Item-spezifische, datengetriebene Lernprozesse erklärbar sind und willkürliche Entscheidungen beim Strategiewechsel folglich keine Rolle spielen. Statt dessen deuten die Daten (Reaktionszeiten, Fixationen, Transfer-Fehler) darauf hin, dass Strategiewechsel top-down moduliert sind.

Schlagwörter: Informationsreduktion, Fertigkeitserwerb, Strategiewechsel, Willentliche Kontrolle

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Publications

- A) Gaschler, R., & Frensch, P. A. (2007). Is information reduction an item-specific or an item-general process?. *International Journal of Psychology*, 42, 218-228.
- B) Gaschler, R., Marewski, J. N., & Frensch, P. A. (submitted). Once and for all—How eyes ignore irrelevant information. *Submitted to Journal of Experimental Psychology: Learning, Memory, and Cognition*, February 2009.
- C) Gaschler, R., & Frensch, P. A. (2009). When vaccinating against information reduction works and when it does not work. *Psychological Studies*, 54, 42-53.

Introduction

Theories of skill acquisition suggest different mechanisms to account for the effects of practice on task performance. This dissertation will focus on accounts that root gains in performance in qualitative changes in the effective task structure which have been referred to as strategy changes (e.g., Cheng, 1985; Logan, 1988, 1992; Rieskamp & Otto, 2006; Siegler & Stern, 1998). For example, Cheng (1985) linked improvements in task performance to “a restructuring of the task components so that they are coordinated, integrated, or reorganized into new perceptual, cognitive, or motor units.” According to this account, people reduce the mental effort required to perform a task by changing from one task strategy to another one, while other sources of practice effects for instance, involve strengthening a given procedure (e.g., Anderson, 1982; MacKay, 1982). Practice-related strategy change constitutes both a hallmark of successful skill acquisition and a constant source of operator errors in technical systems. Often a reduction of effort based on strategy change is welcome, for instance, when small children switch from a cumbersome, effortful finger-counting strategy to a less effortful and much quicker memory-retrieval strategy when they are adding two numbers (e.g., Siegler, 1988; or Lemaire & Reder, 1999, for selection of shortcut strategies in arithmetic by adults). Yet, the literature on human-machine interaction contains many examples of operators starting to use shortcut strategies and therefore overlooking critically important information (e.g., examples in operating trains and aircrafts in Dekker, 2002, or power plants in Reason, 1990).

In order to help ascertain that people reduce cognitive effort quickly when warranted but remain vigilant when needed, researchers need to better understand how skill acquisition leads to the reduction of cognitive effort. In this work, we focus on a particular type of strategy optimization that frequently occurs as a consequence of practice in a specific type of task environment and that has been labeled “Information Reduction” (e.g., Haider & Frensch, 1996, 1999a, 1999b, 2002, for related proposals also see Anderson, Matessa, & Douglass, 1995; Dreisbach & Haider, 2008; Green & Wright, 2003; Logan & Etherton, 1994; Rehder & Hoffman, 2005). The research on Information Reduction emphasizes practice-related changes of *which* rather than *how* information is being processed. Information Reduction applies in situations in which tasks contain both relevant and irrelevant information, and denotes a change from a strategy that is based on exhaustive processing of all elements of a task to a strategy that skips the irrelevant task components. Behavior in line with the notion of Information Reduction has been described in educational psychology (Gaeth & Shanteau, 1984), sports (Helsen & Pauwels, 1993), car driving (Underwood, Crundall, & Chapman, 2002), air traffic control (Niessen, Eyferth & Bierwagen, 1999), and in many other domains.

In the current dissertation, I am concerned with the question if people reduce information processing one by one for different stimuli or, alternatively, decide once to discard certain aspects for all stimuli. Consider privacy issues in online shopping as an example. You might be concerned about your personal data being transferred to third parties for marketing purposes or even identity theft. Maybe you feel more secure about your privacy being protected when you shop on a familiar website you have trusted before than on an unfamiliar one. Would you at least glance at the link to the privacy policy page in the latter case? Vu et al. 2007 reported eye movement data suggesting that users are rather likely to skip privacy information, even though they value the issue highly in self-report measures. Surprisingly, there was no association between how well known the particular websites were to the users and whether the privacy policy link was clicked, or at least fixated. Suggesting item-general Information Reduction, some participants consistently ignored privacy information across different websites, while other participants consistently checked this information on all sites.

Measuring Information Reduction

Much of the existing research on Information Reduction has been conducted using the Alphabet Verification Task (AVT, Haider & Frensch, 1996). In this task, participants are asked to indicate whether or not letter strings on a computer screen follow the alphabet (Figure 1). The strings (e.g., G [4] L M N O P) consist of a letter-digit-letter triplet (e.g., G [4] L, while the digit indicates that four positions in the alphabet have to be skipped) and a varying number (0, 1, 2, 3, or 4) of additional letters (e.g., M N O P). Strings contain both task-relevant and task-irrelevant information. The triplet part of the strings is task-relevant, whereas the additional letters are effectively irrelevant for the participants' task because errors never occur in these letters. In most experiments on Information Reduction, participants are not informed about this characteristic of the task.

Using the AVT paradigm, the present work employed multiple measures of Information Reduction. First, Information Reduction was measured in terms of the dependency of participants' RTs on string length (string length effect). At the beginning of training, valid longer letter strings result in longer verification times than shorter strings. As soon as participants ignore the task-irrelevant information, however, reaction times no longer depend on the length of the strings as responses are based on the consideration of the string triplet alone. Second, in a transfer block after practice, the formerly irrelevant letters were made relevant. As violations to the alphabetical order now also occurred outside the letter-digit-letter triplet, the proportion of transfer errors indicated the extent to which the formerly irrelevant information was indeed overlooked. Furthermore, irregular

strings were employed throughout practice in one of the experiments, that allowed to track the time course of Information Reduction both based on transfer error rates (for irregular trials) and RTs (for regular trials). Finally, we employed eye tracking data to measure the extent to which irrelevant information was fixated on at the trial level. On the one hand, eye tracking data show how fixations on irrelevant parts of the strings change with practice. In addition, changes in the fixations prior to stimulus onset are of interest. While anticipatory saccades early in practice are expected to aim at screen locations where the irrelevant part of the string is likely to appear, later in training participants might direct their gaze toward the relevant part of the string instead.

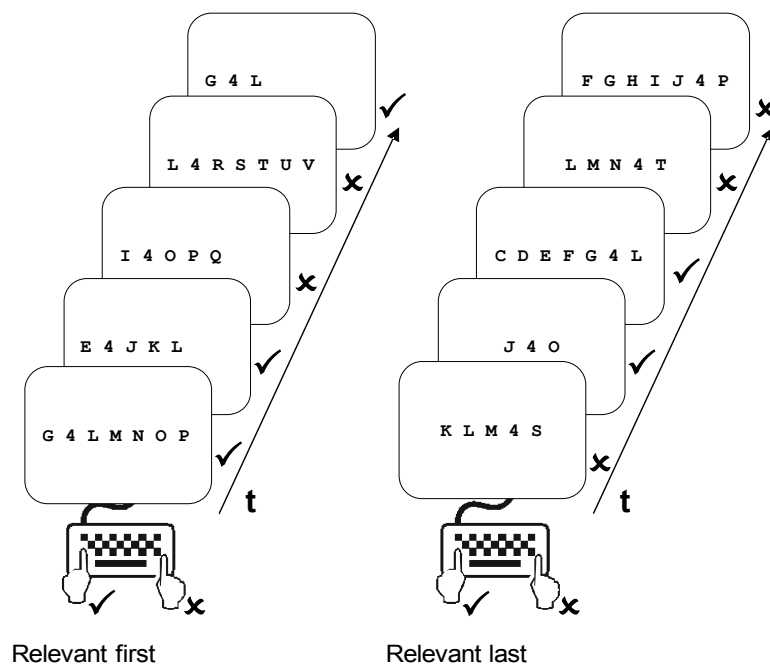


Figure 1. Schematic illustration of the Alphabet Verification Task. The “relevant last”-version was used in Gaschler, Marewski, and Frensch (submitted). In the other experiments the relevant letter-digit-letter triplet came first and the irrelevant additional letters were appended as a suffix. The assignment of left vs. right keys to indicate that a string followed the alphabet (✓ for valid strings) vs. did not follow the alphabet (✗ for invalid strings) was counterbalanced across participants.

Theoretical Goals

The present research aims to distinguish between two broad categories of theoretical perspectives on strategy change. According to one view, strategy change in general, and information reduction in particular, is a consequence of automatic, data-driven processing. Although most of the theories have been developed to explain different types of strategy change (most often a change

from an algorithm-based strategy to a memory-retrieval strategy), their assumptions apply to information reduction as well. For example, in Logan's (1988, 1992, Logan & Etherton, 1994) Instance Model, a strategy change (i.e., from counting through the indicated number of letters to retrieving from memory the correct response for an alphanumeric stimulus) occurs when the control of performance is passed from algorithm-based processing to memory-based processing. In the Instance Model, task processing is initially controlled by an algorithm but each task plus the respective solution is stored separately as an instance in memory as well. Every encounter with a task activates the algorithm that can be used to solve the task, as well as each instance that has been associated with the task in the past. Key to the Instance Model is the assumption of a race between the algorithm and the stored instances in which the fastest process wins the race, that is, determines the response. Due to the obligatory accumulation of memory instances, the probability that the memory retrieval wins the race increases with practice resulting in a gradual transition from algorithm-based to memory-based processing. Thus, following the Instance Model, a strategy change from algorithm-based to memory-based processing occurs when the number of memory instances is large enough to control performance; the strategy change is thus entirely data driven (for similar views see, e.g., Nosofsky & Palmeri, 1997; Palmeri, 1997, 1999; Rickard, 1997, 2004; Siegler, 1988). The Instance Model and related theoretical views all share the assumption that strategy changes during task practice are the result of automatically occurring learning mechanisms and do not depend on top-down modulation.

However, recent data challenge the assumption that strategy change is an inevitable consequence of task practice as would be implied by data-driven accounts (Haider & Frensch, 1996, 1999b, 2002; Haider, Frensch, & Joram, 2005; Newton & Roberts, 2000; Touron & Hertzog, 2004a, 2004b; White, Cerella, & Hoyer, 2007). Rather, this research suggests that a strategy shift is at least in part top-down and voluntarily controlled. For example, results of experiments with the AVT have shown that with practice, participants become increasingly likely to abruptly switch from a strategy involving processing all elements of a task to a processing-relevant-elements-only strategy (Haider & Frensch, 2002; Haider et al., 2005). This involves that irrelevant parts of strings are no longer fixated (Haider & Frensch, 1999a). When new but structure-equivalent strings are presented after the shortcut strategy has been adopted, Information Reduction is transferred to the new strings (Haider & Frensch, 1996, 2002). Finally, speed-accuracy instructions affect how quickly during practice the shortcut strategy is adopted (Haider & Frensch, 1999b) in the first place and how it is applied later. Changing from accuracy to speed instructions within an experiment turns on Information Reduction whereas the opposite change in instructions switches it off. Together, these results suggest that the strategy shift leading to Information Reduction is at least partly

mediated by a deliberate, top-down decision.

The two alternative theoretical interpretations of strategy change in general, and information reduction in particular, data driven mechanism vs. top-down mechanism, are not compatible with each other. However, as of yet, the available empirical evidence does not clearly favor one of the two accounts over the other. For example, the Instance Model of skill acquisition can offer alternative explanations for some of the findings that have been interpreted as evidence for a top-down influence on Information Reduction. According to the Instance Model, for example, the string length effect in the AVT does not disappear with practice because irrelevant information is strategically discarded from processing, but rather because participants come to memorize the entire string in one trace together with the corresponding answer.

Fortunately, however, the data driven vs. top-down explanations of Information Reduction make different predictions that can be tested empirically. Specifically, one of the empirically tangible differences between the two positions concerns the predicted influence of a frequency-of-presentation manipulation (see e.g. Harris, Murphy, Rehder, 2008) on Information Reduction in the AVT. According to the data-driven view, Information Reduction is item-specific. That is, adopting the novel processing-relevant-elements-only strategy in the context of the AVT for one letter string does not imply adopting the same strategy at the same time for a different letter string. Rather, whether or not the novel strategy is adopted for a particular letter string is determined, exclusively, by the number of prior encounters, respectively the strength of the memory representations of the letter string. Consequently, letter strings that are practiced very often in a training phase are more likely to result in Information Reduction than are letter strings that are presented only rarely.

The top-down view of strategy change does not predict string-specific Information Reduction. Rather, it predicts that once a participant has decided to switch to the processing-relevant-elements-only strategy, this strategy should be applied to all letter strings — regardless of how often they have been practiced before. In other words, the top-down view predicts that Information Reduction is item-general.

Accordingly, the present research tested whether Information Reduction is an item-specific or item-general process. The latter distinction has been discussed by other researchers with respect to various other types of changes in performance (e.g., Allen & Brooks, 1991; Anderson, 1993; Harris et al., 2008; Jiang & Song, 2005; Mayr & Bryck, 2005; Logan & Stadler, 1991; Nosofsky, Clark, & Shin, 1989; Opfer & Siegler, 2007; Schmidt & Besner, 2008; Smith, Langston, & Nisbett, 1992; Strayer & Kramer, 1994a; Touron, 2006; Verguts & Notebaert, 2008; Wright & Whittlesea, 1997). Rather than applying a transfer phase after considerable practice, we experimentally manipulated the frequency with which individual letter strings in the AVT were encountered in each block. Given

that past research has suggested that Information Reduction is item-general after practice (Haider & Frensch, 1996, 2002) as it was applied to a transfer block with novel strings, we were interested in whether Information Reduction was item-general vs. item-specific while it developed. Presumably, when starting with well-known items, information reduction needs considerable practice to be generalized to less-known items, as well. It might take considerable training to guide fixations away from irrelevant aspects of tasks. For instance, Smilek, Solman, Murawski, and Carriere (2009) found that participants fixated on words in a Stroop task at the optimal viewing position for word reading, even though word reading was by instruction the very process to be avoided in this task.

We used the AVT for mainly two reasons. First, this task is derived from and is very similar to alphabet-arithmetic, a task that has often been used in research supporting purely data-driven models of strategy change (e.g., Logan, 1988, 1992; Rickard, 2004). New manipulations can therefore challenge these theories within their original context. Second, the AVT offers strong means to ensure that a frequency-of-presentation manipulation indeed successfully influences representation strength. Participants can switch from a strategy of counting through the letters indicated by the digit in the triplet to (faster) memory retrieval of the correct response. Therefore, frequently and infrequently presented strings can be expected to differ substantially in reaction time (RT), as for the latter the memory representation necessary for the alternative strategy will be available only later in the experiment. Depending on the theoretical view, one or two strategy changes of interest can take place over the course of practice in the AVT. A transition from processing the irrelevant letters to discarding them and / or a transition from algorithmic to memory-based evaluation. The Instance Model (Logan, 1988, 1992) and related theoretical views would suggest that entire strings become memorized. Information Reduction would be a by-product of the automatic acquisition and use of item-specific memory traces (see above). If however Information Reduction is item-general, then two types of strategy change would underly the performance improvements in the AVT: first, a transition from the algorithmic to the memory strategy concerning the triplets and, second, a shift from processing to ignoring the additional letters.

Predictions of Item-specific and Item-general Perspectives

If Information Reduction is item-general, then processing of irrelevant aspects of frequent, infrequent, and novel strings will be reduced at the same time and at the same rate during practice. This should result in a parallel reduction of the RT-based string length effect over practice blocks (1). The additional amount of time needed to process long and medium strings (that are longer than short strings solely due to additional irrelevant characters) will decrease in parallel for frequent, infrequent, and novel strings. In a transfer phase after practice, equal rates of errors due to

overlooking of violations of the alphabetical order in the no longer irrelevant part of frequent, infrequent, and new strings are expected (2). Also, fixations to the irrelevant parts will be reduced in parallel and to the same extent over blocks of practice independent of string frequency (3). Item-general Information Reduction will take place rather abruptly and at the same point in time for all alphanumeric strings (4). Finally, Information Reduction will not be fine-tuned to spare specific strings in case some of the strings during practice consistently contain irrelevant information, while other strings are not consistently valid outside the triplet. Thus, depending on the amount of trials in practice in which Information Reduction leads to an error, it will either be impeded for all strings or will take place for all strings – in this case at the cost of an increasing error rate of trials with strings that are invalid outside the triplet (5).

Different predictions for Information Reduction result from data-driven, item-specific models of strategy change. If Information Reduction is item-specific, then processing of irrelevant aspects of frequent strings will be reduced faster across blocks of trials as compared to processing of irrelevant aspects of infrequent strings. The RT-based string length effect and fixation time to irrelevant letters should decline faster across blocks for the frequent as compared to the infrequent strings. Accordingly, transfer error rates should be higher for frequent as compared to infrequent and novel strings. Data-driven item-specific Information Reduction should take place gradually rather than abruptly. As the responses to infrequent strings will rarely be based on memory-retrieval, algorithmic processing might in most cases avoid that invalid letters outside the triplet are overlooked if they occur in infrequently presented strings.

Results

Manipulation check – Representation strength was successfully varied

Before turning to the results on Information Reduction, it has to be emphasized that our manipulation checks indicated that representation strength of the strings was successfully varied in all experiments. In terms of RTs, frequently encountered strings were generally processed faster as compared to the infrequent or singleton strings. The relevant parts of infrequent and singleton strings accumulated longer fixation times and resulted in larger pupil dilation as compared to the relevant parts of frequently encountered strings.

Reduction of the string length effect over blocks (1)

Extent and time course of Information Reduction were first compared for a control group that practiced every alphanumeric string twice per block and an experimental group in which item frequency was varied within-persons (Gaschler & Frensch, 2007, Experiment 1). In the latter group,

half of the strings were presented once per block (infrequent strings) and the other half of the materials was presented three times per block (frequent strings); the overall amount of practice (i.e., number of trials) was identical for the two groups. Unannounced to the participants, the letters outside the letter-digit-letter triplet always followed the alphabetical order and were therefore effectively irrelevant. At the beginning of practice, longer strings (containing more irrelevant letters) yielded longer RTs as compared to shorter strings, indicating that irrelevant information was processed at the beginning. The RT-advantage of shorter over longer strings disappeared with practice. Importantly, Information Reduction happened at the same time and to the same extent for the strings presented once, twice, and three times per block, suggesting that Information Reduction was item-general.

The other experiments included in the present dissertation replicated and extended the above finding of equal reduction of the string length effect for strings of different frequencies of presentation over practice blocks. For instance, Experiment 2 in Gaschler and Frensch (2007) added singleton strings (each just presented in two consecutive blocks) to the frequent and infrequent strings. Nevertheless, the string length effect decreased in parallel over blocks for the frequency classes. In the last practice block, the RTs for short, medium, and long strings essentially did not differ from each other. Thus, the additional irrelevant letters in the medium and long strings did not draw additional processing time.

While usually participants are not informed about the underlying task regularities, Gaschler and Frensch (2009, Experiment 1) told participants upfront that the letters outside the triplets would be consistently valid and thus irrelevant for *some* of the strings. Actually, during practice *all* strings were alphabetically valid outside the triplet. One might expect the explicit instructions to lead to item-specific Information Reduction at least early in practice. Participants might show Information Reduction on the frequently repeated strings at the beginning of the Experiment as for those strings it should become clear early on that the letters outside the triplet are consistently valid. For the infrequent strings, however, Information Reduction might start in later blocks or not at all. While for instance the third exposure to an infrequent strings happened in Block 3, each frequent string had already been practiced three times in Block 1. However, participants showed the same time course and extent of Information Reduction for frequent and infrequent strings, again suggesting that Information Reduction is item-general. Furthermore, compared to Gaschler and Frensch (2007) where Information Reduction was incidental, the explicit instruction led to an earlier reduction of the string length effect. Extra time associated with the processing of the irrelevant letters was present in Block 1, but already absent in Block 2.

Equal rates of transfer errors for strings of different frequencies (2)

When in a final transfer block, the formerly irrelevant letters outside the triplet contained violations of the alphabetical order, high rates of transfer errors were observed. For instance, confirming the impression that Information Reduction was effective to a high extent, 40 out of 60 participants in Gaschler and Frensch (2007; Experiment 2) failed to correctly verify all or all but one of the irregular strings in the final transfer block. Importantly, the rate of transfer errors did not differ for strings that had been repeated with different frequency during the practice phase. This was true also when an experimental manipulation of the validity of the letters outside the triplet led to a reduction in the overall rate of transfer errors (Gaschler & Frensch, 2009, Experiment 2). Therefore, the equal rates of transfer errors in Gaschler and Frensch (2007, Experiment 2, as well as in 2009, Experiment 1) are unlikely to be due to a ceiling effect.

Equal fixations to the irrelevant letters for strings with different frequencies (3)

Eye tracking data were employed to measure Information Reduction at the level of single trials in Gaschler, Marewski, and Frensch (submitted). We employed a frequency manipulation like in Gaschler and Frensch (2007, Experiment 2) involving frequent, infrequent, and singleton strings and changed the layout of the strings such that the irrelevant letters came first and were followed by the triplet. While in the string layout used in Gaschler and Frensch (2007, 2009), Information Reduction meant that the relevant triplet was likely to be fixated first and processing was stopped after this, the present setup tested whether Information Reduction would result in fixations being directed at the relevant part of the strings from the very start of the trials (instead of just avoiding further fixations at the end of processing in a trial).

This was indeed the case as with practice, participants showed the same reduction of fixation time on the irrelevant part of the frequent, infrequent, singleton strings. Furthermore, we observed a practice-related change in fixations prior to stimulus-onset, which per se has to be regarded as item-general. In later blocks, anticipatory saccades were increasingly often directed toward where the relevant part of the strings was likely to appear (instead of where the string was likely to start). Those anticipatory saccades toward the right part of the screen were not corrected when infrequent or singleton strings appeared. Even when the triplet of a novel string was fixated at the onset of a trial, there was no re-checking of the irrelevant additional letters. The fixations on the irrelevant part of frequent, infrequent, and singleton strings disappeared at the same time in practice.

In an additional step, we employed mathematical modelling to analyze and interpret the data. Practice-related strategy change has often been described by continuous practice functions that involve a “trial” parameter (e.g., power law of practice in Logan, 1988, 1992). While referring to it

as “trial”, the Instance Model and related data-driven, item-specific accounts of strategy change imply that the trial parameter in essence mirrors the number of prior encounters with the specific item present in the current trial, rather than how many trials have passed so far in the experiment (irrespective of the specific stimuli involved). As past research on strategy change in skill acquisition usually did not vary the frequency with which different items were presented per block, the number of prior encounters with a specific string and the number of prior encounters with *any* string was not dissociated experimentally as it was in our design (compare e.g., Lee & Anderson, 2001, who proposed a power law decrease in fixation time to irrelevant screen locations).

Bolstering the above results by mathematical modeling, we used the trial by trial measure of fixation time in the irrelevant letters, combined with a manipulation of frequency of presentation to specify what the “trial” parameter meant in Information Reduction. In a first step, we compared fits of two versions of the power function that differed by the specific constitution of the trial parameter (see above). As the strategy change toward skipping the irrelevant letters was item-general, it was the number of prior encounters with any string rather the number of prior encounters with the specific string shown in the present trial that drove Information Reduction.

Time course – abruptly and at the same point in time for all strings (4)

In a second step of mathematical modeling in Gaschler, Frensch, and Marewski (submitted), we tested whether the reduction of fixations on irrelevant aspects of the task does indeed follow a continuous practice function (specifically the power law, as e.g. suggested by Lee & Anderson, 2001) or a discontinuous practice function. The latter possibility was put forward by research on Information Reduction that observed drops in RT of over 1,000 ms from one block to the next (Haider & Frensch, 2002; Haider et al., 2005). We found, indeed, that participants stopped to fixate the irrelevant letters abruptly and consistently for the different strings that occurred in the task. For most participants, fixations on the irrelevant letters of frequent, infrequent, and singleton strings stopped at approximately the same trial.

Item-general Information Reduction at the cost of errors (5)

It might be surprising that the irrelevant parts of infrequent and singleton strings were ignored to the same extent as were the irrelevant parts of frequent strings. In all experiments, our manipulation checks indicated that we had successfully varied the representation strengths of the strings. Yet, there was no modulation of the string length effect by frequency. The additional processing time that medium and long strings took as compared to short strings was identical for strings of different frequencies and showed the same dynamics and amounts of reduction with practice.

Although these results should be surprising from data-driven perspective on skill acquisition, one may object that item-general Information Reduction came at no cost in the above research (i.e., the letters outside the triplet were consistently irrelevant during practice). This was changed in Gaschler and Frensch (2009, Experiment 2) as we focused on how Information Reduction could be avoided. Costs of item-general information reduction were imposed by occasionally placing errors in the letters outside the triplet. Again, half of the strings were repeated three times per block and the other half once per block. For one group of participants, a sixth of the trials with *frequent strings* were presented with a violation of the alphabetical order outside the triplet while such irregular strings never in practice occurred in the set of infrequent strings. For the other group of participants, the placement of violations to the alphabetical order outside the triplets was reversed. It affected a sixth of the trials with *infrequently* repeated strings, while all the frequently repeated strings were regular. While the proportion of irregular copies of original strings was constant between the experimental groups, the absolute number of irregular strings amounted to 16 vs. 48 of 384 trials in the practice phase.

Information Reduction was impeded in the condition with the irregular strings in the frequently repeated set. This condition showed few errors on the irregular trials. In the condition with the irregular infrequent strings, however, Information Reduction took place at the cost of an increase in the rate of errors in irregular strings over blocks. Differing *between groups*, the number of trials with irregular strings was the variable that affected whether or not Information Reduction occurred. However, *within experimental groups* there was no difference in Information Reduction for frequently vs. infrequently repeated strings. This was evident as the rate of errors on irregular trials in the transfer phase did not differ for frequent vs. infrequent strings within experimental groups. In the transfer phase, irregular strings occurred both in the set that during the the practice trials contained vs. was free from irregular strings. Thus, it was not the case that participants showed Information Reduction on the strings that were consistently valid outside the triplet while they avoided strategy change in case of those strings that in some trials were irregular. Information Reduction was item-general despite costs in terms of errors.

The string length effect based on RTs of correctly verified valid strings confirmed the above conclusion. The string length effect differed between experimental groups but did not differ within experimental groups for strings of different frequencies. The string length effect decreased with practice in the condition with irregular trials in the infrequent set (in parallel for valid frequent and infrequent strings). However, it remained constant in the experimental group with the higher amount of trials showing an irregular string.

Summary and Discussion

Conclusions based on work in the included publications

While it has been long acknowledged *that* people tend to ignore information they deem irrelevant, the experiments in the summarized publications add to the efforts of the literature on Information Reduction to specify *how* people discard information from processing. This knowledge is important on practical grounds as it, on the one hand, suggests how to secure that people reduce cognitive effort to use their resources efficiently when warranted and, on the other hand, predicts how Information Reduction can be impeded when information that is often irrelevant is occasionally of vital importance. On theoretical grounds, the data help to differentiate between two classes of theoretical views on strategy change in general and Information Reduction specifically. The results are inconsistent with models that base strategy change exclusively on data-driven processing for they regard the mandatory strengthening or accumulation of memory traces as the sole driving force of strategy change (e.g., Logan, 1988, 1992; Nosofsky & Palmeri, 1997; Palmeri, 1997, 1999; Rickard, 1997, 2004; Siegler, 1988). Rather, our data suggests the involvement of top-down voluntary decisions in strategy change (see also Haider & Frensch, 1996, 1999b, 2002; Haider et al., 2005; Newton & Roberts, 2000; Tournon & Hertzog, 2004a, 2004b; White, Cerella, & Hoyer, 2007).

Discarding of irrelevant information sets in abruptly with equal strength and consistency for all structure-equivalent items (i.e., alphanumeric strings) in a task – irrespective of whether the strings have been practiced often or rarely or are even novel. It is not the case that the novel strategy to discard the irrelevant letters from processing first has to be practiced with the set of material it has evolved on before a transfer to novel material is possible. The results suggest that Information Reduction is item-general as it develops in practice and thereby extend research that used transfer blocks with novel strings at the end of training (Haider & Frensch, 1996; 2002; see Logan & Klapp, 1991, for a different type of strategy change).

It is important to stress, that indicators derived from RT, fixation, pupil dilation and post experimental rating scales¹ all showed that we successfully manipulated the representation strengths of the strings (or at least of their relevant parts as the results on Information Reduction suggest). People processed the relevant parts of the alphanumeric strings differently depending on the frequency of presentation per practice block. As strings with different rates of presentation were randomly intermixed within the blocks, so were presumably trials that were solved algorithmically by counting through the indicated number of letters in the triplet and trials in which memory-

¹ Post-experimental ratings on string frequency were collected in an unpublished study of 35 participants that mirrored the design of Gaschler, Marewski, & Frensch (submitted), but lacked eye-tracking.

retrieval indicated the correct answer (compare e.g., Logan & Klapp, 1991; Rickard, 2004). Assuming that the strategy that was applied to the relevant part of the strings (i.e., algorithm vs. memory retrieval) varied from trial to trial, in principle, there thus should have been a basis to vary Information Reduction trial by trial. Also, the literature on the item-specific proportion congruent effect in the Stroop task suggests that people can pick up item-specific contingencies between relevant and irrelevant information (e.g., Schmidt & Besner, 2008).

Mirroring earlier reports of rather inflexible top-down driven strategy control by Strayer and Kramer (1994b), we found that people showed item-general Information Reduction even at the cost of errors when these would have been avoided by item-specific strategy selection. When participants were presented with one set of strings for which Information Reduction was permissible and another set for which it was not warranted, people exhibited Information Reduction on *all* strings, when this general strategy resulted in few errors. However, there was no Information Reduction at all when ignoring the additional letters would have led to more frequent error feedback. Presumably, there are substantial costs of switching the processing mode from trial to trial (e.g., Kray & Lindenberger, 2000; Meiran, 1996) leading to a voluntary decision to use either the strategy involving complete processing or the processing-relevant-elements-only strategy for all strings.

Broadening the Perspective on Strategy Change

Item-general learning of the triplets

Based on the above considerations, a re-analysis of RTs for trials in which only relevant information was presented (short strings, triplet only) seemed warranted to explore the source of practice gains for the relevant part of the strings. In order to better understand the context in which item-general information reduction works on the irrelevant string parts, we were interested in the skill acquisition processes affecting the triplets. Data from 151 participants who practiced half of the strings three times per block and the rest of the material once per block was re-analyzed for this purpose (Gaschler & Frensch, 2007, Experiments 1 & 2, Gaschler & Frensch, 2009, Experiment 2). The main effect of frequency on RT reported in all Experiments (i.e., our manipulation check of that representation strength was successfully varied) suggested that processing of the triplets was affected by the amount of practice with the particular letter-digit-letter triplets per block. While processing-changes concerning the irrelevant string parts were exclusively accounted for by item-general practice effects, this was apparently not the case for the processing of the triplet part. Frequent triplets were processed faster in comparison to infrequent triplets.

Data-driven, item-specific theories of skill acquisition predict that the efficiency in processing

a specific triplet depends on how often it has been encountered before. For example, in Instance Theory (Logan, 1988, 1992), the likelihood that an answer can be retrieved from memory and does not have to be produced algorithmically (e.g., by counting) depends on how often the specific problem (i.e., alphanumeric string) has been responded to before. This suggests to plot the RT data of the triplets grouped by indexing the encounters with the particular strings (instead of a block-wise analysis as was presented in the included publications). As frequent strings had been repeated three times per block and infrequent ones once per block, the first four data points of the infrequent strings correspond to Blocks 1 to 4 respectively, while the first four encounters with frequent strings happened in Blocks 1 and 2.

As Figure 2 shows, RTs were reduced faster across the four encounters with *infrequent* as compared to the first four encounters with frequent strings. The infrequent strings apparently profited from item-general practice in the many other trials in between. In an ANOVA incorporating the first four encounters of the infrequent and frequent strings, this pattern led to an interaction between frequency and encounter [$F(3, 450) = 12.59, MSE = 701451, p < .001$]. Furthermore, main effects of frequency [$F(1, 150) = 47.86, MSE = 1756436, p < .001$] and encounter [$F(3, 450) = 160.94, MSE = 1157937, p < .001$] reflected the fact that infrequent strings were overall processed faster in the first four encounters than frequent ones and that RTs declined with the number of encounters. Thus, item-specific practice alone could not account for the triplet processing, either. Rather, a mixture of item-specific and item-general processing must be assumed. The possibility that participants might start to develop mnemonics and actively encode items was already acknowledged by Logan and Klapp (1991, in their case with respect to alphabet-arithmetic; see for example also Sahakyan, Delaney, Kelley, 2004; Shing, Werkle-Bergner, Li, & Lindenberger, 2008) and is in line with post-experimental interviews collected for the research presented here. Participants might have produced the correct response algorithmically and then have actively encoded the string together with the response for later memory retrieval. Different participants reported to have started to encode the triplets at different points in practice (e.g., in different blocks) rather than from the very start of the experiment. For instance, they mentioned that they were first waiting to see whether the pool of the alphanumeric strings would stay the same, before starting to memorize. While the first few encounters with the frequently presented strings would likely already have occurred for most participants (e.g., the first three encounters in Block 1) when active encoding started, most of the encounters with the infrequent strings were yet to come. This offers an explanation for the higher decline in RT per encounter found for the infrequent as compared to the frequent strings. Presumably, the former differentially profited from active encoding.

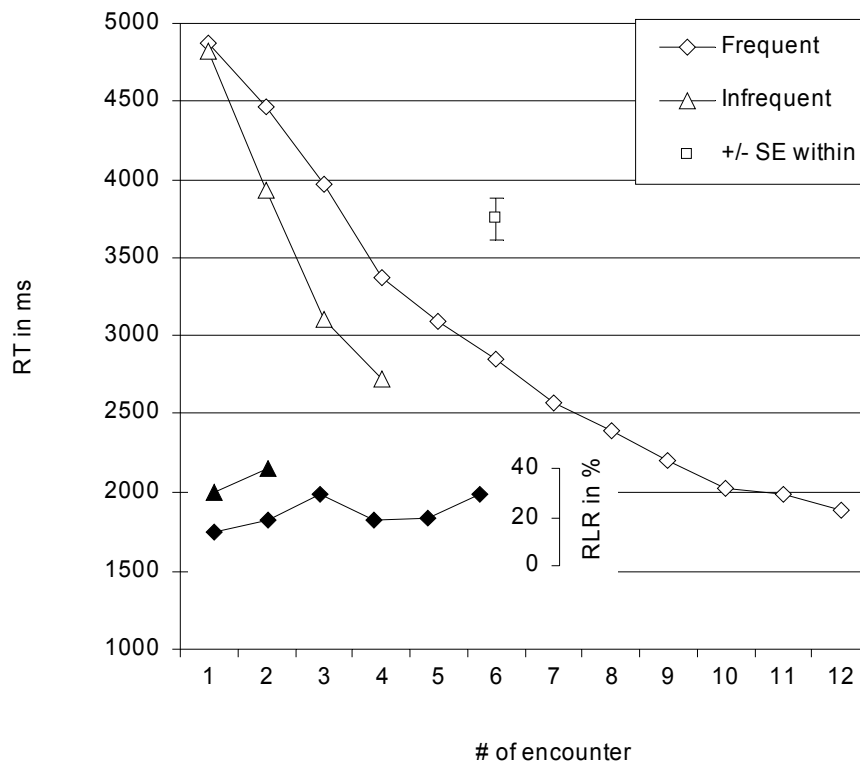


Figure 2. Reanalysis of RTs to trials with short strings (relevant part only, means of individual medians) of 151 participants. Instead of an analysis based on practice block, the data are re-arranged by indexing the encounter of the strings on the x-axis (compare e.g., Mayr & Bryck, 2005, Experiment 4). While the first three encounters with each of the frequent strings took place in Block 1, the first three encounters with the infrequent strings happened in Blocks 1, 2, and 3. Purely item-specific, data-driven learning would predict a complete overlap of the two practice curves. The error bar represents the within-subjects standard error of the mean based on the interaction of frequency and encounter (Masson & Loftus, 2003). The lines with the filled symbols depict the non-parametric relative learning rate (RLR) based on the RT at Encounter 12 as an estimate of the asymptote. Simulations have suggested that RLRs of the first half of the practice curve are relatively robust for overestimations of the true asymptote.

The practice curve of the 12 encounters with the frequently repeated items offers yet another interesting observation. Data-driven theories of skill acquisition would assume that the largest gains in performance happen early in practice. Logan (1988, 1992), for instance, proposed that RTs should follow a power function. Descriptively, such a function would be characterized by a decreasing relative learning rate. The early encounters with the material led to the acquisition of a higher proportion of what has yet to be learned (till asymptotic performance) as compared to later encounters (compare Heathcote, Brown, & Mewhort, 2000). Such a decrease in relative learning rate is however, not observed in the present data (compare² and Figure 2). Presumably, many

² Note that unpublished data suggest that the performance at the 12th encounter is close to the asymptote. Furthermore, the introduction of novel triplets after at the end of the experiment led to RTs comparable to the ones at the

participants did not start active encoding early in practice. If it is assumed that the strategy change from algorithmic solution to responding based on memory-retrieval was distributed over the entire practice phase across the participants, then a major contribution to overall performance would have worked against the power law. In line with this assumption, the result at the aggregate level shows a much shallower curvature than would be expected by a power function (compare Haider & Frensch, 2002 for how the distribution of abrupt changes relates to the curve describing aggregated performance).

Taken together, the results on triplet processing suggest that not only Information Reduction concerning the suffixes, but even the transition from an algorithmic to a retrieval-based strategy concerning the triplets is subject to an item-general top-down strategy selection.

Data-driven and yet item-general?

A brief discussion of alternative interpretations of the above evidence seems warranted. Are there purely data-driven accounts that could explain item-general Information Reduction? One option would be to argue that allocation of attention to screen positions is learned. According to this view, Information Reduction would be item-general because shifts of attention or eye movements to screen positions are learned and this knowledge would be item-general (i.e., shifts to specific locations rather than to specific characters). For instance, in the model by Kruschke (2001, 2003; see also Kruschke, Kappenman, & Hetrick, 2005, for a model test including eye tracking data), a learning mechanism changing feature-response associations is working together with a learning mechanism that alters the attentional weights of features quickly, thereby shutting on and off the impact of certain feature-response links depending on their success in predicting rewarded categorizations. By this account, the screen positions carrying the relevant part of the alphanumeric strings would with practice receive more attention and the irrelevant letters would receive less. Consequently, task-relevant information (the triplet) would be in the focus of attention and infrequent or even novel information outside the focus would have the role of an unattended, task-irrelevant distractor and therefore would not influence performance (compare e.g., Gronau, Sequerra, Cohen, & Ben-Shakhar, 2006).

It is unlikely that the above considerations could give a full account of the data on Information Reduction that are presented in this dissertation. Rehder and Hoffman (2005a) used eye-tracking in a classification task in which the features differed in relevance and were spatially separated. They found that for many participants, classification errors and fixations to screen positions carrying the

very beginning of the experiment. However, the speedup from the 1st to the 2nd encounter with the novel triplets showed larger gains as compared to the 1st and 2nd encounters at the beginning of the experiment. Supposedly, many participants employed active encoding when they see the novel strings for the first time at the end of the experiment, while this approach was not yet in effect in the first block for many participants.

unpredictive features ended abruptly. Consistent with the view that eye-movements were following rather than driving the change in the classification process (i.e., discovery of a rule), the classification errors ended just *before* the fixations on the unpredictable features ceased. Furthermore, manipulating the predictive value of spatial positions, Haider and Frensch (1999a) documented Information Reduction in a condition in which the position of relevant triplet was varied on a trial-to-trial basis. Yet, Information Reduction was somewhat slower when the triplet was placed first or last in the strings, varying randomly from trial to trial, as compared to conditions that kept the position of the relevant information constant within participants. In the eye tracking study included in the present work, we found item-general Information Reduction despite the fact that strings were presented centered on the screen. As a consequence, the triplets appeared in the middle of the screen when strings were short, but on the far right of the screen when strings were long. The absolute location of the relevant string part thus varied considerably from trial to trial.

Based on the above considerations, *absolute* screen positions therefore are not a candidate learning target for an item-general, data-driven learning mechanism and one could try to suggest data-driven models that learn *relative* screen positions. In a line of research that is currently conducted, we investigated strategy change in a situation where neither absolute nor relative screen positions were predictive³. In each trial, participants saw a cloud of copies of one letter that were randomly distributed over the screen. In a first experiment, participants responded left vs. right depending on whether the number of copies of the current letter was odd or even. Some letters were used five times per block and others just once per block. According to a hidden regularity, all trials with more than four letters demanded the response odd (or even, counterbalanced across participants). After some practice, participants stopped counting the instances of the letter in large clouds, as the very fact that it was a large cloud already suggested the answer. RTs and transfer errors showed that the strategy change was item-general. Interestingly, this was true even in a second experiment, in which the responses were item-specific. Rather than pressing a left vs. right on the keyboard for odd vs. even numbers of letters, participants responded with the regular key of the specific letter used in the current trial. To indicate whether the number of instances was odd or even this key was pressed once vs. twice (again counterbalanced). Although the strategy change occurred later in practice, as compared to the version with just two response buttons, it was nevertheless item-general, despite the item-specific mode of responding. Of course, such a manipulation could also be employed in the AVT to explore the boundary conditions of item-general Information Reduction in that task.

3 If anything, the sheer amount of shifts of attention or fixations in a trial was predictive of the answer.

Studying Information Reduction after it happened outside the lab?

In an article currently under revision, Gaschler, Mata, Störmer, Kühnel, and Bilalić explored whether the flicker change blindness paradigm (Rensink, O'Regan, & Clark, 1997) can be employed to study which information people process on food packages. On each trial two versions of a photograph with a food product were shown in alternation, interrupted by a brief blank. The two versions differed by one type of product information. For instance, in a given trial the best-before date might have been constantly appearing and disappearing until the participant indicated the location of the change in the current picture with a mouse click. Of special interest were the change detection times for product information only recently introduced to the market (certain health claims, organic food label of the European Union). Interestingly, older participants (who were presumably more experienced consumers) showed differentially longer detection latencies on the newer product information while their detection latencies on established product information were not higher than that of younger participants.

One interpretation of these findings is based on a view of grocery shopping from a skill acquisition perspective. For the older participants, proficiency in the features needed to find the milk and select the right sort at the supermarket might have reached asymptotic levels before the new product information was introduced. Given a habitual set of search-features, it might therefore have been more difficult to attend to other product information, even in a lab task that explicitly demanded this.

Voluntary vs. involuntary performance changes

The above interpretation suggests that voluntary control of features to-be-attended to might be rather limited once practice in selecting one set of features has occurred. In a similar vein, the literature on the set effect suggests that known solutions to problems can block the discovery of better ones. Testing proficient chess players, Bilalić, McLeod, and Gobet (2008a) showed that problem solving ability was reduced to that of players three standard deviations lower in skill level by the presence of the non-optimal solution. The standard solution to a chess problem (that was most likely voluntarily acquired earlier in the carrier of the players), prevented the participants from finding a better solution. Even though the players *knew* that they were to search for a solution other than the standard approach they spotted right away, they could not direct their fixations away from the fields on the board associated with this standard solution (Bilalić, McLeod, & Gobet, 2008b). The best solution was, however, quickly discovered if the standard approach was rendered unsuitable (by placing a bishop in such a position that the first move of the standard solution was impossible).

While there is good evidence that Information Reduction is under voluntary control when it takes place, other forms of change in task performance change have been documented that most likely are purely data-driven and lack voluntary control. Implicit sequence learning might be considered as one example. At the beginning of an implicit sequence learning experiment, participants respond mainly stimulus-driven as in any choice-reaction experiment, while later on, response control shifts from the stimuli to the memory representation acquired due to the predictable sequence (compare Tubau, Hommel, & López-Moliner, 2007). Often, an abrupt and large performance gain is observed which can be linked to participants becoming able to verbalize the sequence and use explicit sequence knowledge to speed up responding (Frensch & Rüniger, 2003; Rüniger & Frensch, 2008). However, gradual and involuntary shifts in control of performance seem to take place as well. For instance, Destrebecqz and Cleeremans (2001) showed that participants fail to follow an instruction that asks them to produce any sequence but the one they were previously exposed to. Thus, even though control of responding has shifted from the stimuli to the sequence knowledge, voluntary control is lacking. In a similar vein, Perlman and Tzelgov (2006) demonstrated acquisition and transfer of sequence knowledge that was neither required nor beneficial for task performance.

In sequence learning tasks, there is usually a one-to-one correspondence between one sequence of stimuli and one sequence of responses (but see Goschke & Bolte, 2007). Accordingly, it can be argued that shifts in control are rooted in the strengthening of encounter-specific (i.e., stimulus-specific and / or response-specific) knowledge rather than in the acquisition of processing strategies applicable to many stimuli (compare Doane, Sohn, & Schreiber, 1999) and therefore do not constitute examples of strategy change per se. Therefore, it is important to note that strategy change outside voluntary control has also been documented in tasks other than the AVT, that dissociated learning effects involving the specific material and learning effects involving processing steps. Examples involve Woltz, Gardener, and Bell (2000) who studied the acquisition and transfer of knowledge concerning the sequence of cognitive operations in the Number Reduction Task and Doane et al., 1999) who investigated the development and transfer of visual discrimination strategies in a polygon comparison task.

It has yet to be established why strategy change under some conditions occurs as a top-down voluntary decision while under other conditions, voluntary control seems to be lacking. Presumably, the availability of verbal codes could be an important variable. The power of instructions to configure task-sets has for instance been documented by Kray, Eenshuistra, Kerstner, Weidema, and Hommel (2006) and by Wenke and Frensch (2005) and self-instructions likely have a similar power. Accordingly, spontaneously generated verbal knowledge of a task regularity might be causal in

producing voluntary changes in the task set. This alleged verbal-executive route of strategy change would be impeded when verbal descriptions are difficult to generate. For instance, participants might not have spontaneously generated verbal descriptions of their approaches to differentiate between the arbitrary polygons of Doane et al., 1999) as the stimuli were neither verbal nor easy to describe verbally. For situations in which verbal coding is likely, the involvement of the latter in the generation of top-down control might be investigated including neurophysiological data. So far, results point to the involvement of the medial temporal lobe in the acquisition of processing sequences (e.g., Rose, Haider, Weiller, & Büchel, 2002) and the right dorsolateral prefrontal cortex in strategy change (e.g., Rose, Haider, Büchel, Verleger, 2001). Temporal lag correlations with activity patterns in verbal areas might help to test the link between speech and voluntary strategy change.

Finally, apart from being informative with respect to the choice of interventions fostering or impeding Information Reduction, the finding that Information Reduction is top-down modulated also renders important the inclusion of personality characteristics thought to influence top-down control in future studies. This involves the constructs of behavioral approach vs. behavioral inhibition (Gray, 2004; Gray & Burgess, 2004), promotion vs. prevention focus (Förster, Higgins, Bianco, 2003; Higgins, 2000) and need for cognition (Caccioppo, Petty, & Kao, 1984).

Conclusion

In showing that Information Reduction develops item-generally, the work collected in this dissertation delivers further empirical arguments countering models that root strategy change in cognitive skill acquisition exclusively in data-driven, item-specific learning. Rather, the results speak for the involvement of top-down voluntary control in strategy change. Participants *decide* to ignore parts of tasks they deem irrelevant and adhere to this approach when confronted with less well known or even novel material. Future work might try to explain why some forms of strategy change are apparently under voluntary control while others are not.

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Erklärung zum Zustandekommen der Arbeit

Hiermit erkläre ich,

- dass ich die vorliegende Arbeit selbstständig und ohne unzulässige Hilfe und ohne Benutzung anderer als der angegebenen Hilfsmittel und Quellen angefertigt habe,
- dass ich mich nicht anderwärts um einen Doktorgrad beworben habe und keinen Doktorgrad in dem Promotionsfach besitze, und
- dass ich die zu Grunde liegende Promotionsordnung vom 03.08.2006 (Amtliches Mitteilungsblatt 34/2006) kenne.

Berlin, 25.02.2009

Robert Gaschler