Effects of Set-Size on Switch-Cost

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Abstract

This study investigated how a set-size manipulation (as published in Fitzgibbon, Cragg & Carroll, 2014) could affect switch-cost in a switching-task, and the relation to working memory capacity. A student sample of 29 participants was recruited. Results revealed that decreasing the set-size might facilitate switching. Working memory capacity was negatively correlated with repeating a task (i. e., with not switching), when the set-size was large. The results are relevant to theoretical top-down and bottom-up explanations of switch-cost, and have practical implication for the further use of task-switching paradigms.

Keywords: task-switching, set-shifting, set-size, switch-cost, flexibility, perseveration

Effects of set-size on switch-cost

Adapting one's behaviour flexibly to changing environmental demands is crucial. The nervous system is adapted for this function, but still it can be difficult to overcome strong habits. We tend to get stuck in behaviours and mental sets, even if we want to overcome them. Having changed our password, we might still type in the old one. We might perseverate in old ways to solve a problem, that is, to reach our goals. Both switching and perseveration are functional, but in various circumstances. Standing at the ATM, we efficiently type in the code we have used for years, and not much effort is required for this. But, having changed the code recently, automatically typing in the old one without further thought, is clearly not efficient. It might even be detrimental if we perseverate on typing in the old one, if the bank keeps the card. More cognitive work is needed when switching to a new code. We have to overcome the strong memory of the old code and the motoric habit of typing in the old code, and we have to actively keep the new code in our mind. Combatting this interference of the old code, might possibly depend on aspects such as for how long we have had the old code and how often we change our code. It might also depend on how many different cards we use. Probably, individual differences in cognitive capacity are related. In this study I intended to experimentally investigate how the size of a mental set affects switching.

The theoretical background will start with what we know about executive functioning, especially its sub-component of flexibility, and the related task-switching paradigm and its measure of switch-cost. It further explores cognitive processes that lead to flexibility and to inflexibility. It emphasises the importance of representation of the rule (e. g., a code or a password) and so-called complex rule-use, and it also notes the automatic learning of associations, which can stand in the way for flexibility. Finally, it describes how set-size manipulation can explore all these issues. To my knowledge, there is not much research looking on set-size in task-switching.

Executive Functioning

The important cogntive functions that are needed to control and change our behaviour adaptively, like when standing at the ATM with the new code, are referred to as executive functions (or sometimes cognitive control). Faced with this new situation, it is not adaptive to rely on the automatic and well-learnt behaviour we have done so many times before. A new strategy is required. The executive functions are referred to as top-down processes, which means that our intentional effort is required. When standing at the ATM, this environment automatically triggers the old code and the behaviour of typing in that one. These processes are referred to as bottom-up processes. They are our stimulus-driven responses from the environment. For successful behaviour, such as getting the money, it is required that our top-down executive functioning overcomes the bottom-up interference from the strong association between standing at the ATM and the representation of the old code, an association that might have been built up for years.

These demanding situations involve three core executive functions, which are referred to as flexibility, inhibition, and working memory (Diamond, 2013; Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). Inhibition is the ability to suppress one's attention to irrelevant and interfering information, or to stop prepotent responses. A prepotent response can be the automatic behaviour of typing in the old code. Without inhibition we would be at the mercy of conditioned responses and stimuli in the environment that steal our attention (Diamond, 2013).

Working memory is about actively maintaining and working with information (Miyake et al., 2000; Smith & Jonides, 1999; Baddeley & Hitch, 1994). At the ATM, we must actively represent what is relevant in this particular situation, that is, the new code and not the old one. It is important to note that it is not short-term memory, which is simply to hold something in mind (Diamond, 2013). It also includes working with something other, while holding the information in mind (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005). It involves updating information and monitoring information.

Further, with working memory it is possible to relate information in order to derive a general principle (Diamond, 2013). It allows for seeing relations between what seems unrelated, and also to pull apart items from the integrated whole. An essence can get abstracted from something. Instead of seing red, blue, green, yellow, we might consider this as colour. Our knowledge hence gets conceptual and not only perceptual (ibid.).

Flexibility is the ability to switch attention between several representations, or to switch between tasks, strategies, and responses (Miyake et al., 2000). It builds on the two other core executive functions, and it develops later (Diamond, 2013). It concerns ability to change perspectives or strategies. In order to change perspectives, it is necessary to inhibit the previous perspective and load the new one into working memory. Flexibility is the opposite of rigidity. One has to be able to switch successfully between the possible codes. The three core executive functions clearly are intertwined with each other, even though they are separable (Miyake & Friedman, 2012). Since the topic of this thesis is switching, I will continue describing flexibility. I will describe methods for measuring switching-ability and theoretical explanations for flexibility and inflexibility (or perseveration).

Flexibility

Flexibility is required for example when a strategy does not work, and one has to try another strategy. To rigidly persevere with the old strategy is not adaptive. Sometimes one indeed intends to switch, but fail to do so, because the old habit is automatised.

The most used approach to study cognitive flexibility is the task-switching paradigm (Meiran, 2010; see also Grange & Houghton, 2015; Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp & Koch, 2010; Vandierendonck, Liefooghe & Verbruggen, 2010; and Monsell, 2003 for exhaustive reviews of the task-switching paradigm). In these tasks, participants have to switch their attention and their responses between different perceptual stimuli, and the measure of interest is the switch-cost. Switching typically is more effortful and takes longer time, than choosing to do the same thing as before (i. e., to stay on the task). It is also typical to make more errors. In other words, switching comes at a cost. Reasons for why switching costs more, might be the interference from the earlier task (like the old code mentioned above), and it might be trouble to load the new task into working memory.

In a switching task, the participant typically might get two cards to choose from. The two cards might be blue and red. The experiment-leader tells the participant to choose either blue or red, and after responding, the participant gets a new set of cards to choose from. The rule (i. e., whether blue or red is correct to choose) typically changes over this run of sets, and this is supposed to reflect switching. The rule can also be to choose blue every second time, for example, which therefore requires more working memory, because the participant is not cued explicitly from the experiment-leader concerning the right rule.

The cost of switching compared to repeating a task, is typically seen on two levels. It is not only seen when comparing the response to each single card. It is also seen when comparing entire runs of these sets of items to choose from, and runs where there is no need to switch (i. e., when the participant can repeat taking the blue each time). Other stimuli than colours might be used in task-switching, like a number and a letter displayed together, where the participant is to choose between responding to the number or the letter. Another version is to get a sequence of numbers, where the task is to add 3 and subtract 3 from every, for example, second trial.

It is not only flexibility and working memory that are important in these task-switching paradigms. Interference of the irrelevant task (such as the old code in the ATM-example) and the inhibition of responding to this, is a crucial feature. There is a conflict. The former response to the blue card might stand in the way for responding to the red one, especially if blue have been the correct colour for several consecutive trials. The task of switching between red and blue is relatively simple, in typical experiments the conflict is more complex, because of more dimensions than just one (colour, in this case). The target card might represent both a colour and a shape (i. e., two dimensions). Then there might be a blue rectangle, a red rectangle, a blue triangle, or a red triangle, on that card. The set-size is much larger.

The increased conflict and complexity is seen in how this kind of task-switching paradigm is structured. The target card comes up with two option cards to choose from. The two options always accord to the target card on one dimension, but not the other. For example, if the target stimulus is a red rectangle, and the rule is shape, then the two options to choose between would be a blue rectangle and a red triangle. In this case, the correct response is the blue rectangle, because shape is the rule. Note that both options accords on one of the dimensions, and this is the interfering conflict. The only cue is the rule, so it is crucial to keep the rule in mind. The interference from the conflicting stimulus has to be suppressed, in order to perform the task successfully. This kind of task-switching paradigm therefore allows for complex manipulations to explore flexibility.

Increasing the dimensions and the options within each dimension, allows for manipulations of how the size of the mental set might affect switching. The example above had two dimensions (colour and shape) with two levels within each dimension (red and blue, and rectangle and triangle). This can be called a 2x2-design. The number of total individual exemplars consequently are four, that is, all the possible distinct combinations. So the number of these categorical dimensions decides how many possible exemplars there are. Five colours and five shapes would render 25 different stimuli. This is the set-size (Fitzgibbon, Cragg & Carroll, 2014).

An early predecessor of this task-switching paradigm is the Wisconsin Card-Sorting Task (Berg, 1948; Grant & Berg, 1948; Milner, 1963). In this, each card typically can vary on three dimensions, and with four levels on each, so the set is 4x4x4. The dimensions are colour, shape, and number of items, so one card can have three yellow stars on it. Only one dimension is correct, and the conflict comes from the alternative dimensions that interfere. The only cue for which dimension to attend to, is the rule. A successful performance also requires suppression of the irrelevant rules. With a larger set-size, there obviously becomes more stimuli to attend to, and consequently more effort is needed to switch correctly, due to the interference.

As mentioned above, the switch-cost is the measure of how well the participant switches (Grange & Houghton, 2015; Rogers & Monsell, 1995). The cost of switching, compared to repeating the task, shows in slower responding and more errors. The switch-cost is taken as evidence for that switching is more cognitively demanding than not switching. Further, the faster responding when not having to switch possibly reflects habitual learning through repeating a task (e. g., when having typed in the same code for years). In other words, there are two possible theoretical explanations for the phenomenon of switch-cost; top-down control and bottom-up associative learning.

Switch-cost as an operationalisation of flexibility has generated much research. It has been found that despite given ample time for preparation, and despite being cued, participants' switch-cost does not diminish completely (Meiran, 1996). Children might even perseverate on the old rule, despite explicitly and repeatedly being told which one is the correct rule (Zelazo, Müller, Frye & Marcovitch, 2003). The top-down and bottom-up theories trying to explain the costs of switching, will be described below. One can divide the theories in two parts; the ones that explain how processes behind switching contribute to flexibility, and the ones that explain how processes behind switching contribute to rigidity (Meiran, 2010). The latter ones are obstacles in form of habits, while the former ones ensure successful goal-achievement (by combatting the inner obstacles). In other words, it is about the automatic bottom-up processes and top-down control processes.

Automatic Processes Leading to Inflexibility

The habitual automatic processes driven by stimuli rather than the organism's own intentions, are mainly so-called task-set inertia, and associative learning (Meiran, 2010). The task-set is the mental representation of the whole task-situation; what the task is, that this problem has to be solved (ibid.). One has a goal to reach. It is critical that the task-set has to be updated when the task changes (Grange Houghton, 2015; Meiran, 2010). The task involves making a response, preferably an appropriate one. At the ATM, the task is to get money out of the machine. One has a mental representation of this goal. If having changed the code recently, there are not only one code represented in one's mind. One has to monitor the task to perform it successfully. Or in the laboratory, one's task might be to sort the particular card on the dimension shape. Task-set change leads to slowed responding, that is, slowed behaviour. If the mental representation of *x* changes, the response-time slows. Task-set inertia subsequently is when the representation of the task lingers on; the memory-traces stay. (Logan 2003; Allport, Styles & Hsieh, 1994). The activation of the mental representation carries on. The switching from one task to another involves two parts; inhibiting the old and now irrelevant task, and activating the new and relevant task (Meiran, 2010). Task-set inertia implies that the representation of the first task has not been properly inhibited and the new task not properly activated. The former rule of sorting cards according to colour, lingers on and interferes with the new rule of sorting to shape. This contributes to the switch-cost.

Apart from task-set inertia, associative learning is a major obstacle for switching. Stimulus-set binding (Meiran, 2010; Waszak, Hommel & Allport, 2003; Allport & Wylie, 2000) refers to the binding between task-sets and the stimuli on which the task is executed. The idea is that the set gets (automatically) retrieved from memory when the participant re-encounters the stimuli. Associative learning is useful because we learn to perform tasks more automatically; they become habitual and do not require the same amount of effort as new tasks. Sometimes however, the particular stimulus might require a new task, and the old stimulus is no longer relevant (Meiran, 2010). Standing at the ATM with a new card and new code, the memory trace of the old code possibly gets retrieved. This habitual response to heavy learnt stimuli-associations can be quite strong. In order to overcome these habitual responses, and the above mentioned inertia in task-set relevancy, intentional control-processes are needed (ibid.). These control processes, to which I now turn, contribute to flexibility instead of inflexibility.

Control Processes Leading to Flexibility

Control in switching-situations requires intentionality, inhibition, and monitoring (working-memory). A control-process contributes to flexible goal-directed behaviour by helping to overcome the learnt habitual behaviour (Meiran, 2010).

There are three major control-processes in the task-switching literature; task-decision and goal-maintenance, inhibition, and monitoring (ibid.). The subjects must know what the task is, and that knowledge may come from one's own memory as well as from an external cue. They also have to hold that representation of the task in working-memory. Secondly, they must inhibit the first task in order to perform the new one. Thirdly, monitoring of changes is important.

After this description of processes facilitating and processes hindering switching, there will be a description of the importance of representation of the task, to combat interference and inflexibility. Active representation is important, and higher-level representation is also important.

Representation of the Task-Set

Representing the task is crucial. The subcomponents in any task for us, be it in an experiment or in real life, are initially to *represent* the task, then to *plan* how to execute it, followed by actual *execution*, and finally *evaluation* of the how well it worked (Zelazo et al., 2003). Rigid representation of objects can lead to rigidity in problem-solving and hinder creativity (ibid.).

Inflexibility is often studied with the concept of perseveration. Perseveration is regarded as “the repeated production of an action or thought” (Zelazo et al., 2003, p. 2). The concept of perseveration is common in developmental research and in clinical research, and has a negative sense to it. It is in these studies not used as meaning being perseverative to accomplish something, or persevere through something. In card-sorting paradigms, it is regarded as perseveration if the participant repeats to sort cards according to the old rule; the measure is called perseverative errors. Patients with damage to the prefrontal cortex tend to perseverate (Zelazo et al., 2003). Children perseverate on such tasks (ibid.), and their prefrontal regions indeed are not yet fully developed (Crone, Donohue, Honomichl, Wendelken & Bunge, 2006; Casey, Tottenham, Liston & Durston, 2005).

Inflexibility can occur at the level of representations and at the level of responses (Zelazo et al., 2003). Representations are about representation of task-sets and responses are about motor-programmes. The former one is about difficulty to inhibit an incorrect task-representation and activating a correct one, and the latter one is about failure to inhibit an incorrect response despite having activated a correct task-intention.

An example of infant-perseveration is the A-not-B-error, where children tend to search for a toy at a previous location A, even when they have seen it being moved to location B (ibid.; Marcovitch & Zelazo, 1999). It is interpreted as that they have difficulty representing the object's location to override the prepotent response (i. e., the representation of the previous location). During development, representational flexibility as well as the response-control increase. The increased representational flexibility (i. e., better ability to change perspectives) is suggested to reflect the development of a more complex hierarchical structure of rule-systems.

Hierarchical Representation of Rules

Complexity-theory tries to explain executive function and its development (Zelazo et al., 2003). The development of executive functioning is characterised as increased complexity in terms of a hierarchical structure of rule-systems. When reflecting on the rules one represents, it is possible to represent them in relation to other rules, and to embed them in higher-order rules. A conditional statement is dependent on the satisfaction of another condition. A rule is embedded under another rule and controlled by it. Increases in embedding means more complexity of the complete rule system that has to be kept in mind (working-memory) for a task. More complex rule-systems allow more flexibility when deciding between conflicting rules, as opposed to perseveration and stimulus-driven control.

The typical task-switching paradigm of sorting cards according to a rule, illustrates the logic of complexity-theory. Two lower-level rules could be "*if* the card is blue, *then* put it here" and "if the card is red, then put it there". The higher-order rule accordingly would be "sort the card according to colour". This strategy allows for more successful card-sorting. If having sorted some red and blue cards, it would be impossible to sort a green card eventually, when the only options seem to be red/blue. Representing the stimuli as *colour* though, allows for accurate sorting when the green card shows up. This increasing complexity of hierarchical rule-systems also allow for successfully sorting conflicting stimuli, which is typical in these paradigms. If the target card is a red rectangle, and the two options two choose from are a blue rectangle and a red triangle, then it would be impossible to sort according to a lower-level rule such as blue triangle. Having the representation of the higher-level rule though, (for example, shape), will tell you which of the two options are correct (in this case, the blue rectangle).

The development of rule-use can be mapped to sub-regions of the prefrontal cortex and their development (Bunge & Zelazo, 2006). Apart from increased flexible rule-use, memory and inhibition develop through childhood and adolescence for successful executive functioning. The three intertwined core executive functions are mainly related to prefrontal cortex (Smith & Jonides, 1999). Executive functioning and its related brain areas mature later than other areas, and decline earlier in life (Logan, 2003). Working memory might be especially important for flexible rule-use, as described in the task-switching paradigm. Working memory makes possible to see relations between items and to derive general principles from these (Diamond, 2013). Apart from this abstraction-ability, it also becomes possible to tease out details from an integrated whole (ibid.).

Maintaining Representations During Interference

The maintenance of representations in an active state is particularly important when there is interference (Kane & Engle, 2002). It is under interference-rich contexts that habitual responses and irrelevant information is more likely to be retrieved. There are individual differences in this working memory capacity. Reliable and valid measures for this general cognitive capacity are working memory span tasks, or complex span tasks.

Simple memory tests, so-called simple-span tasks, have a storage-component with the purpose of measuring the capacity of storage, for example remembering a list of numbers (i. e., short-term memory). Complex span tasks have an additional processing-component also, with the purpose to interfere with the storage-component (i. e., working memory). It might be about remembering a list of digits while doing mental arithmetic. This kind of task therefore is suitable to investigate how differently interference affects people, when they perform a cognitively demanding task, such as switching. Individuals with lower working memory span scores are more susceptible to interference, than individuals with higher scores (ibid.). Individuals with high spans are more affected though by strong interference, that is, when the information has to be kept in a highly active state. It can be interpreted as that low spans do not engage that much attentional effort at all and consequently do not lose anything of it either. Individuals with low spans tend to rely more on automatic processing, instead of attentional control.

Abstract (hierarchical) task-representations help to guide behaviour when there is no particular cue elicited from the environment regarding an appropriate response (ibid.). The representations are actively maintained. If not, behaviour will be perseverative or inappropriate in general. The active maintenance of task-sets has the effect of inhibiting interference. In task-switching paradigms, the participant can be cued about the correct rule/dimension, or it has to keep the rule in mind, like when being told in the beginning to switch every third trial, for example. This cuing has become common in task-switching research (Meiran, 2015). The purpose is to control for the use of some general cognitive capacity. One is interested in measuring flexibility, and not how well the participant keeps the rule in mind. By cuing, one minimises the need for working memory, and can therefore more easily isolate how well the participant switches.

Individual differences in working memory capacity can reliably predict individual differences in executive tasks (Kane & Engle, 2002). It has been found that among healthy adolescents, working memory span tasks correlate with performance on switching in a typical card-sorting task (Lehto, 1996, Experiment 1). Perseveration showed marginal negative correlations, so failure to switch (i. e., perseveratively respond to the old rule) meant low working memory capacity, and success in switching meant high working memory capacity. It is important to note that in this study, the rule was not explicitly cued on every trial, so one might question whether this result concerns actual switching, or working memory.

Size of the Set

As mentioned earlier in this theoretical background, the task-switching paradigms may differ on number of dimensions and number of levels of each dimension. This reflects the entire mental set or task-set. This has not been considered especially much in research. It is surprising, since this perceptual part is a major feature in these paradigms. The theoretical explanations for switch-cost might be informed by investigating set-size more.

The maintenance of the irrelevant mental set interferes with successful switching. An association has been built up between the old stimulus and response. This association, this set, stands in the way when changing to a new behaviour. But such strongly learnt associations between stimuli and responses might make switch-cost disappear under certain circumstances (Kray & Eppinger, 2006; Waszak, Hommel & Allport, 2003; Allport & Wylie, 2000; Rogers & Monsell, 1995). It has been found that switch-cost decreased using a small set-size compared to when using a large set-size (Kray & Eppinger, 2006). This is simply because associations develop between stimuli and responses, so what seems as faster switching in fact is a practice-effect. It is therefore a risk in task-switching research, to not be aware of this. When seeing a decreased switch-cost (i. e., difference between switching and repeating), it might be about representing the particular associations between the exemplars, instead of switching between the higher-levels dimensions. Each single exemplar is displayed more often with a small set-size. The task-set is differently represented, in other words. It has been argued that a sufficently large enough set-size is needed to avoid associative learning to build up (Rogers & Monsell, 1995). Then there will be less repetition of the stimulus and response associations, and consequently less possibility for strengthening of these.

In Kray and Eppinger's study (2006), a set of 4 exemplars in total, was compared to a set of 96 exemplars in total. There were two dimensions to switch between, more specifically animals vs. non-animals, and one-syllable words vs. two-syllable words. They found age differences for the small set-size; old adults had slower response-times than young adults. Age-differences in switch-cost has been found in studies with small set-sizes (e. g., Mayr, 2001; Meiran, Gotler & Perlman, 2001). It has not been found with larger set-sizes (e. g., Kray & Lindenberger, 2000). The bindings between stimuli and responses thus seem stronger in children as well as old adults (Hommel, Kray & Lindenberger, 2011).

Another study showed that this increased binding that arises from a small set-size increases the need for control (Kray, Karbach & Blaye, 2012). The bottom-up associative learning therefore dynamically interacts with top-down control processes. The interference was more seen in elementary school children compared to young adults. It can be explained by the finding that children are more stimulus-driven and that they are worse at representing and maintaining higher-order task-rules (Zelazo et al., 2003). In the study (Kray, Karbach & Blaye, 2012), the set consisted of two dimensions, and varying number of items of each dimension, more specifically two of each dimension, or 24 of each dimension. This rendered a set-size of 4 and a set-size of 96, as in Kray and Eppinger's study (2006). The dimensions was animal/thing and coloured/white.

A recent study investigated the relative roles of the bottom-up and top-down processes in task-switching (Fitzgibbon, Cragg & Carroll, 2014). The small set was 2x2, more specifically two colours and two shapes. The large set-size had nine colours and nine shapes; a total of 81 individual stimuli. The first experiment found that switch-cost was greater for the small set-size than for the large set-size. The switch-cost correlated negatively with three childhood age-groups. The second experiment varied set-size in two blocks; blocks where the rule (shape or colour) repeated on every trial, and block where the rule switched. It was suggested that the top-down processes was initiated in the repetition-block, while the bottom-up processes occurred in the switching-block. This way, they could compare the two theoretical explanations. The results supported the bottom-up account, and they failed to find support for the top-down account. It was found that a large set-size during switching led to smaller switch-cost, compared to a small set-size, suggesting that bottom-up associations might have been taken place during the small set-size. Increasing the set-size therefore led to better switching. If a large set-size during the non-switch block had led to smaller switch-costs, this would have suggested that higher-level rule-representation had been taken place (i. e., representing the stimulus as colour rather than blue, red, etc.).

For children, the set-size typically is 2x2 (Zelazo et al., 2003). The purpose is to make the task as simple as possible (Kray & Eppinger, 2006). Even for adults, the task-set is relatively small; 4x4x4 in the Wisconsin Card-Sorting Task, which makes 64 exemplars. The three studies show that using a small set-size comes at a cost.

To my knowledge, there are not many studies investigating set-size in task-switching. Further, a small set-size seems to decrease switch-cost, which is suggested to reflect the effects of associative learning and the subsequent need for cognitive control. But regarding the theories of increased abstraction in rule-representation, there should be support also for that a large set-size facilitates switching. I therefore aimed to study how set-size affects switch-cost, in a typical task-switching paradigm. I used the same task as Fitzgibbon et al. did (2014, Experiment 1), where the participant is cued on every trial to minimise other cognitive demands than flexibility. Executive functioning is fully developed first in adulthood. It declines early, so relatively young adults is the most suitable age group. Earlier studies have shown support for that bottom-up processes hinder switching. Engaging healthy adults that are better in executive functioning should show support for higher-level rule-representation, as in large set-size. Individual differences in working memory capacity should be related to such a finding.

My research question was: How does set-size affect switching? Based on earlier theory I had these hypotheses:

1. Set-size should affect switch-cost, as measured by response-times.

1a. Large set-size should lead to less switch-cost, due to better abstraction of rules.
1b. Small set-size could lead to more switch-cost, due to stimulus-response bindings. However, this hypothesis is not clear, due to evidence that bindings engage more cognitive control.
2. Working memory capacity should be negatively correlated to response-times in switching.
2a. This relation should be mostly seen to small set-size, due to the larger interference.

In general, switch-blocks should be slower than non-switch blocks, and switch-trials should be slower than non-switch trials, in line with general theory about switch-cost.

Method

I designed the study in order to manipulate set-size effects on switch-cost, and to explore the relation to working memory capacity. The purpose was to see if perceptual aspects of the stimuli (in the form of set-size) might affect switching ability.

Participants

Participants' (N = 29) age was M = 30.41, SD = 7.35. Females were 17 and males were 12, or 58.6 percent vs. 41.4 percent. All except one were right-handed. None reported colour-blindness. Prior to their participation participants were informed about anonymity and possibility to withdraw at any time. They were recruited from university environments. Participants were randomly assigned to the conditions, and conditions were counterbalanced across participants. There was no missing data. There were 15 participants in a large set-size condition and 14 in a small one. The study was approved by the department, for compliance with ethical standards.

Design

It was a mixed between-within experimental design. The switching-task consisted of three variables, set-size (between-participants), block (within-participants), and trial-type (within-participants). All had two levels. The factor Block was divided in pure blocks (always the same rule) and mixed blocks (the rule switched unpredictably from trial-to-trial). The mixed blocks had non-switch trials and switch-trials. This allows for two measurements of switch-cost, more specifically switch-cost on trial-level, which is the difference within blocks, and also block-level switch-cost, for pure blocks vs. mixed blocks. The dependent variable for measuring switch-cost was response-time in milliseconds.

The set-size condition could be either small or large. The small one had two different colours and two different shapes, which made 4 stimuli. The large set-size had 9 different colours and 9 different shapes, which made 81 stimuli.

Analysis

I computed two mixed-measures analyses of variance to answer the first hypothesis about set-size, and a correlation for the second hypothesis concerning the relation to working memory capacity. The analyses of variance were computed for response-time. One was for block-comparisons (pure blocks and mixed blocks) and the second was for comparing trials (switch-trials and non-switch trials). I report effect-sizes besides probability levels, in order to get a fuller picture of the significance-testing. Means can be found in Table 1.

In order to explore how working memory capacity is related to switch-cost, I compared scores on working memory capacity to the switching-variables. In complex span tasks, I collected partial scores for each individual. I compared the mean-scores on group-level for pure vs. mixed blocks, and for non-switch vs. switch-trials. I did this for both of the set-size conditions. I computed correlation-coefficients, which can be found in Table 2.

Materials

The switching task was the Switching Inhibition and Flexibility Task; SwIFT (Fitzgibbon, Cragg & Carroll, 2014). It was used by permission of the authors. It was presented on a laptop computer in a quiet room at the Psychology Department, and participants responded with a mouse connected to a usb-port on the computer. A left response, that is, when the correct stimulus was on the left part of the screen, was mapped onto the left button of the mouse, and a right response was mapped onto the right button. The stimuli varied on two dimensions; shape and colour. There were nine shapes and nine colours, which made a total of 81 different stimuli (see Fitzgibbon et al., 2014 for examples of stimuli). Response-time and accuracy for each participant were recorded by the computer. The SwIFT lasted approximately 10 minutes.

Three complex-span tasks were used. These were Rotation Span, Symmetry Span, and Operation Span, as in the study by Foster, Shipstead, Harrison, Hicks, Redick & Engle (2015). These include a storage-component with an interfering processing-component, accordingly with theory of working memory capacity. One block from each task was used, which accounts for more than 90 percent of the variance in the full model, which is three blocks from each task (ibid.). The tasks were counterbalanced between participants. Partial scores for each task were collected for each participant. Partial scoring is superior to absolute scoring, in individual-differences research (Redick, Broadway, Meier, Kuriakose, Unsworth, Kane & Engle, 2012; Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005). The tasks should be used together (Foster et al., 2015), so I added the three scores together, and used this total score in the analysis. The tasks in total lasted approximately 45 minutes, and each approximately 15 minutes.

Procedure

Due to minor changes from the original version of the SwIFT, I will offer a full description of my version, in contrast to the complex span tasks, which are freely available for researchers. On each trial in the SwIFT, it appeared a fixation box in the top centre of the screen, and it appeared for 1000 milliseconds. Then the target-stimulus appeared in the box, and stayed for 500 milliseconds. During this time, an auditory cue said either ”shape” or ”colour”. Then two different response-stimuli appeared on the bottom left and bottom right parts of the screen, while the target stimulus remained on the upper part. The task was to choose which of the two response-stimuli was correct, according to what the auditory cue had said. Of the two response-stimuli, one matched the target-stimulus on the shape-dimension, and the other on the colour-dimension. Neither of the response-stimuli was ever corresponding to the target-stimulus on both dimensions. The interference therefore was the two competing stimuli, which corresponded to both options, but only one was correct according to the cue. After a response, the next trial came up. No feedback was given, neither when participants responded correctly or not correctly, further there was no feedback regarding response speed. However, there was a practice-block in the beginning of each pure block, consisting of 4 trials, in which auditory feedback was given in the form of a voice saying ”very good”, or a ”beep”.

There were 2 pure blocks and 4 mixed blocks. The pure blocks had the auditory cue saying either shape or colour on every trial in the particular block; one block always got the shape while the other always got the colour. The two pure blocks were counterbalanced between participants so that every second one got the shape-rule first and the colour-rule next, and vice versa. Each pure block consisted of 9 trials, so 18 trials in total. The stimuli always appeared in the same order for every participant, that is, it was sequentially selected and not randomised in any way. In the large set-size, the stimuli were constrained so that each exemplar within a dimension occured only once as a target stimulus within a block. Further, an exemplar within a dimension never repeated on consecutive trials. There was at least one trial in between a reoccurring dimension. After the two pure blocks followed the mixed blocks, which consisted of 9 trials each. The target stimuli were constrained according to the same logic as the target stimuli in the pure blocks. In the small set size, each target stimulus appeared several times within a block. This is because there were nine trials and only two dimensions (compared to nine dimensions in the large set-size) and consequently there were repetition. This means more stronger priming and consolidation.

The trials in the mixed blocks were non-switch trials and switch-trials, depending on what rule the previous trial had had (stated by the auditory cue). Consequently, the first trial of each mixed block was neither switch nor non-switch. The trials of the pure blocks were neither switch nor non-switch trials, since the rule always was the same (either shape or colour). There were 17 switch-trials and 15 non-switch trials in total, in the task.

In the beginning of the task, the participant was shown an example array of a target stimulus and two response stimuli, and I explained the task and how they were to respond correctly. The stimuli in the instruction, as well as the stimuli in the 8 practice trials (4 in the beginning of each pure block) were not the same as in the trials that were to be recorded from.

Before the pure colour block, a display showed the text ”The Colour Game” and before the pure shape block, it was shown ”The Shape Game”. Before the first mixed block, the display said ”The Colour and Shape Game”. Before the rest of the mixed blocks, a text was shown that reminded participants to respond fast but also correctly. Before the practice blocks, a text said that there would be 4 practice trials where nothing will be logged, and before the ”real” blocks a text said that it is for real and that response time and accuracy will be logged. There was no practice block before the start of the mixed blocks.

After having completed the SwIFT, the participants got the working memory capacity tasks. The tasks were Operation Span, Symmetry Span and Rotation Span and used with permission from Randall W. Engle's Attention and Working Memory Lab at Georgia Institute of Technology. These three complex span tasks were counterbalanced across participants. The three complex span tasks were the shortened versions used by Foster et al. (2015). The full model has three blocks of each of the span tasks, but it has been shown that using one block from each span task accounts for 91 percent of the variance in fluid intelligence, compared to the full model (ibid.). The purpose of using shortened tasks instead of traditional versions, is to prevent researchers from using only single tasks. It is important to use multiple tasks to measure working memory capacity reliably (ibid.).

Each complex span task consists of three parts; a storage-component (i. e., simple span), a processing component, and a storage and processing component (i. e., complex span). The purpose of the processing component is to prevent the rehearsing of the to-be-remembered items, and therefore makes the task a complex span task and not only a storage/memory task. Each part starts with practice trials for the storage and the processing component respectively, and then several sets of trials for the storage and processing components combined (i. e., a complex span task). In the operation span, the distractor task is arithmetic operations, and these come between each item to be remembered, in this case letters. In the Symmetry Span, the distractor task is to judge whether an image is vertically symmetrical, and the storage task is to remember where in a grid a red box appears and in what order. In the Rotation Span, the distractor task is to judge whether a rotated letter is mirrorwise or normal, and the sequence to be remembered is in what order and direction two lengths of arrows are shown (see Foster et al., 2015, for figures).

The number of to-be-remembered items, as well as the distractor tasks, varied unpredictably from one trial to the next. The speed of the distractor displays was adapted to each individual's performance, because during the practice-phase of the distractor task, the response-time is averaged, and during the real trials participants have to respond within 2.5

standard deviations from their average response-time, otherwise the programme goes on to the next set (of a storage component and a processing component).

Results

I first show the results for the first hypothesis, which was about whether manipulation of set-size affects switching-performance. This was hypothesised to reflect theoretical issues of priming (which more likely builds up with a small set-size), and generalisation of higher-level rules (which should be easier with a large set-size). Then I show the results for the second hypothesis, concerning relations to working memory capacity. Adults have developed their executive functioning and should be less susceptible to priming and its interference.

First I show the results from the two mixed analyses of variance where I had compared response-times between the groups. Here, I computed mean response-times. Possible switch-cost is seen when comparing the values in the table. These results and the accompanying Table 1 answers the first hypothesis.

After this first part, I show correlations between the different switching-variables (i. e., switch-cost between blocks and between trials) and working memory capacity. In the correlation matrix in Table 2, results for both set-sizes are shown. These results answers the second hypothesis. In the end, I conclude all results.

Set-Size Effects on Switching

I excluded the first trial from each block in the SwIFT prior to analysis, because these were neither switch trials nor non-switch trials. None of the trials had response-times less than 200 ms. Trials that were more than 2.5 standard deviations away from the individual's mean response-time for that type of trial were excluded (2.5 percent). The participants had accuracy-rates close to 100 percent, whereas the earlier study on children (Fitzgibbon, Cragg & Carroll, 2014) had lower rates. Therefore it would have been unsuitable to perform further analysis of this skewed distribution. The accuracy values ranged from 91 to 100 percent, and the typical was 98. In the response time analysis, incorrect trials were excluded and also the first trial after an inaccurate trial; such trials cannot be considered as definite switch or non-switch trials (Fitzgibbon et al., 2014). The total number of trials entered into the analysis was 1302. Of these, 669 came from large set-size and 633 from small set-size. 428 were from switch-trials and 377 from non-switch trials. 497 came from the pure blocks.

Trial-type (switch and non-switch) and block-type (mixed and pure) were within-participants variables and set-size (small and large) was a between-participants variable. Means for response-time are shown in Table 1.

Table 1

Response-times (in ms) by block-type and trial-type

		Block-type				
		Mixed		Pure		Switch-cost
Set-size	*n*	*M* (*SD*)	95% CI	*M* (*SD*)	95 % CI	
Small	14	519 (122)	[438, 600]	436 (60)	[373, 599]	83
Large	15	626 (168)	[548, 705]	562 (149)	[501, 623]	64
Both	29	574 (155)	[515, 633]	501 (130)	[452, 551]	73

		Trial-type				
		Switch		Non-switch		Switch-cost
Set-size	*n*	*M* (*SD*)	95% CI	*M* (*SD*)	95 % CI	
Small	14	527 (122)	[453, 601]	508 (139)	[410, 605]	19
Large	15	618 (145)	[547, 690]	637 (206)	[544, 731]	-19
Both	29	574 (140)	[521, 628]	575 (186)	[504, 645]	-1

Note. CI = confidence interval.

First I looked on block-level. There was a statistically significant main-effect for set-size, in the sample, $F(1, 28) = 7.22$, $p = .01$, partial eta squared = .21. Not surprisingly, there was also a statistically significant main-effect for block-type on response-times, Wilks' Lambda = .73, $F(1, 28) = 9.9$, $p = .004$, partial eta sqaured = .27. This suggests that there are differences in response-times for mixed blocks and for pure blocks. Set-size affects response-times, which is in line with the hypothesis. More narrowly, the group that got small set-size showed shorter response-times compared to the group that got large set-size, as seen in Table 1. This is seen for both the mixed and the pure blocks. There was no statistically significant interaction-effect between set-size and block-type, Wilks' Lambda = .99, $F(1, 28) = .15$, $p = .7$.

Secondly, I looked on trial-level. There was a marginally significant main-effect for set-size, $F(1, 28) = 3.95$, $p = .057$, partial eta squared = .13. However, and somewhat surprisingly, there was no statistically significant main-effect for trial-type, Wilks' Lambda = 1.0, $F(1, 28) = 0$, $p = .99$. Hypothetically, there should be longer response-times for switch-trials than for non-switch trials. When inspecting the table, it shows that the switch-cost is negative; -19 milliseconds. This would have suggested that switching is not at all a cost then, rather it would be the opposite. Concerning interaction-effects, it was as on block-level above; no statistically significant effect on trial-level, Wilks' Lambda = .96, $F(1, 28) = 1.14$, $p = .3$.

The mean for large set-size overall was 602 milliseconds with a standard-deviation of 49, and for small set-size it was 488 with a standard-deviation of 88. The large set-size condition therefore led to more than a second of slowed switching, compared to the group that got the small set-size condition.

In sum, these findings suggest that there is a set-size effect on response-times, both when comparing pure and mixed blocks, and when comparing non-switch and switch-trials. More narrowly, a small set-size leads to faster responding, that is, better switching-performance. However, it was not possible to see how set-size interacted neither with block-type nor with trial-type. Also important, is that it was found that pure blocks were faster than mixed blocks, but it was not possible to see which trial-type was faster than the other.

Working Memory Capacity: Correlational Evidence

The second hypothesis in this study concerned relations of switching and set-size to working memory capacity. Higher working-memory capacity (WMC) should mean better cognitive control against interference from stimulus-task priming. It should also mean better ability to represent task-rules on higher-level dimensions. The results from the analyses of variance above showed faster responding during a small set-size. This is possible to interpret that priming has been taking place.

I explored how WMC is related to response-times between pure and mixed blocks, and between non-switch and switch-trials. Scores from various WMC-tasks should be aggregated (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005). I therefore added the scores from all three tasks (i. e., Operation Span, Symmetry Span, and Rotation Span) for each individual. I used this new score in the subsequent analysis. This mean span-score for all participants ($N = 29$) was 35.62, with a standard-deviation of 6.77, and the range was 26 – 52. Means for the group that got large set-size was 35.33 (8.03), and the one that got small set-size had 35.93 (5.4).

I computed correlations with response-time, and it was separately for each of the two set-sizes. This rendered several correlations that were statistically significant. The correlation coefficients are shown in Table 2.

Table 2

Correlation-coefficients between WMC and mean response-times (ms) for trial-type and block-type as a function of set-size

	1	*2*	*3*	*4*	*5*
1. WMC	–	-.35	-.30	-.33	-.57*
2. Switch-trial	.06	–	.91**	.97**	.66**
3. Non-switch trial	-.21	.72**	–	.98**	.60*
4. Mixed block	-.09	.92**	.93**	–	.64**
5. Pure block	.16	.43	.27	.38	–

Note. Correlations for large set-size ($n = 15$) are presented above the diagonal, and correlations for small set-size ($n = 14$) are presented below the diagonal.

* $p < .05$, two-tailed.

** $p < .01$, two-tailed.

Of most interest are the ones that significantly correlate with WMC, that is, pure block for the large set-size group, with a coefficient of -.57, which is a strong correlation. This negative correlation suggest that high WMC means shorter response-times, and low WMC means longer response-times. This is in line with the hypothesis, but it is important to note two things. This finding concerns pure blocks. In other words, it was in this sample not possible to find such a correlation for switching (i. e., mixed blocks or switch-trials). Secondly, the finding concerns the group that got the large set-size. That is, with a large set-size there is a significant (negative) relation to WMC, but such a relation could not be found with a small set-size. In sum, high WMC is related to shorter response-times in pure blocks and with a large set-size, and low WMC is related to longer response-times under the same circumstances.

Regarding the other significant correlations, it shows that they are strong, except the ones for pure block in the large set-size. Concerning the hypothesis about a set-size effect, it is worth noting that the positive correlation between non-switch trial and switch-trial is .72 for small set-size, but .91 for large set-size. This difference in strength is not seen for the other significant variables (except pure block then). In other words, the relation between response-times for the two different trial-types is stronger with a large set-size than with a small set-size.

In sum, a significant negative relation between WMC and response-times could be seen for pure blocks, and there is evidence also for the first hypothesis regarding a set-size effect.

Conclusion of Results

According to the first hypothesis, there was an expection to see differences in switching-performance, dependent on the set-size manipulation. There was evidence for a set-size effect when comparing blocks as well as when comparing trials. More narrowly, a small set-size led to faster response-times, well above 100 milliseconds.

The second hypothesis expected a relation between switching, set-size and WMC. It was shown a significant negative correlation for pure blocks and large set-size. Regarding set-size, there was evidence for stronger relations between non-switch trials and switch-trials for the large set-size group, compared to the small set-size.

Discussion

The purpose of this study was to investigate how set-size affects switch-cost, and to explore the relation to working-memory capacity. Based on the theoretical background, I expected that a large set-size would facilitate switching and that a small set-size would hinder switching, as measured by response-times. But a small set-size could engage top-down control, so less switch-cost might be seen in the small set-size too. Further, I expected a negative correlation to working memory capacity, and this would be stronger for a small set-size, in which there is more interference. These hypotheses were based on earlier theory, suggesting that this sample of healthy adults should be better able to cognitively control the interference from a small set-size. They should also be better able to represent the rule on a higher-level dimension.

Set-size did affect response-times, but not as expected. It was the small set-size that had shortest response-times, and not the large one, as expected. There was a negative relation between working memory capacity and repeating the task/rule (i. e., pure blocks as opposed to mixed blocks), more specifically, it was for the large set-size.

Even though it was the small set-size that responded fastest, this result still enlightens the theoretical logic behind the hypothesis. Possibly the repetion of stimulus-response bindings engaged more cognitive control, seen in the faster switching. Earlier theory has also found that small set-sizes lead to less switch-cost. This study therefore confirms what have been found earlier. I did not find what Fitzgibbon et al. (2014) found; that increasing the set-size leads to less switch-cost. In that study, it was found that children were facilitiated in switching, by increasing the set-size and therefore weakening the associations between stimuli. My study on healthy adults shows rather that *decreasing* the set-size leads to less switch-cost. This is reasonable, because an adult sample with better cognitive control than children, would be less helped by increasing the set-size, since they already are quite well at combatting interference.

This result is further enlightened by considering the switching's relation to working memory capacity (WMC). First, the negative correlation was for the large set-size. Second, it was for pure blocks, that is, non-switching or repeating a task. Repeating a task therefore is negatively correlated to response-times, during a large set-size. This means that high WMC is related to low response-times in a block with no switching, while low WMC is related to longer response-times. People with low WMC seem to be negatively affected even on pure blocks, as seen on the longer response-times, compared to people with high WMC. This can be interpreted as if their need for control is so great that they need it even under low-demand circumstances such as when not having to switch. One should not forget though that the other correlations did not turn out significant, so it might be due to power issues detecting significant correlations also for the other variables. In that case WMC had correlated also with switching. WMC has typically been investigated on extreme groups (e. g., taking the 25 percent worst and the 25 percent best), but this sample consisted of students, so the range in WMC is without doubt restricted. This study was explorative however concerning set-size and WMC, so more sensitivity can be designed into further studies.

Concerning that this correlation was seen only for the large set-size, it could reflect the idea that a large set-size means less bindings, and consequently it is not as easy to rely on these automatic processes when responding. Even if the rule is shape on every trial, there still is a lot of stimuli to manage. Low WMC might then be more affected by lack of strong associations between the stimuli. High WMC though, manage to repeat a task fast without relying on such associations, so their response-times are still short, as seen in the negative correlation. Further, a large set-size means more need for higher-level rule representation. This is important for switching, but presumably also for repeating the task, because of all stimuli to manage.

In sum, there was partial support for my hypotheses. The effect-sizes for the significant results were good. The sample was 29 on two conditions, which could be considered as a relatively small sample, but adjusting the probability-level would not suffice to render the values statistically significant.

The task-switching paradigms are used to measure cognitive flexibility. Relatively small set-sizes are used, especially with children. My study confirms the earlier research that exists on this topic. Set-size can affect switching. My study more specifically shows that decreasing the set-size can lead to less switch-cost, and it might be explained with increased cognitive control due to more interference. The negative correlation to working memory capacity (however only for pure blocks) is in line with this reasoning. In further research in task-switching, it therefore is important to take notice of the set-size. Otherwise, flexibility can be masked by other cogntive processes.

One might consider the engagement of a student sample as a limitation. Students have a restricted range in age, socioeconomic status, intellectual ability, and so on. However, my purpose was not to generalise findings to, for example, certain clinical groups. I wanted a convenient sample in order to test my hypotheses about perseveration and switching. When knowing more later on, it is possible to build interventions that might help groups that typically perseverate on these tasks. Certain clinical groups suffer from deficits in executive functioning, which shows as rigid and perseverative behaviour in daily life. Exploring factors that affect perseveration, on a healthy student sample, in the laboratory with an acknowledged paradigm, is a step on the way.

One might also question the number of participants. Indeed, the sample was too small in order to detect interaction effects. However, interesting main effects showed up. These inform about the nature of switching. Future studies can try to look for how the variables interact. It would also be interesting to explore the nature of other aspects of the task-switching paradigm. Such basic components that need to be explored are, for example, how the stimuli are realised (typically as shape and colour), and how the feedback is given.

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