UNIVERSITEIT GENT
FACULTEIT PSYCHOLOGIE EN PEDAGOGISCHE WETENSCHAPPEN

Role of endogenous and exogenous factors in voluntary task switching

Jelle Demanet

Promotor: Prof. Dr. André Vandierendonck

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Proefschrift ingediend tot het behalen van de academische graad
van Doctor in de Psychologie

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CONTENTS

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CHAPTER 1
INTRODUCTION

'My first act of free will shall to believe in free will'

– William James

In most situations in daily life, people have the feeling that their actions and choices are caused by their own will or intentions. To most people this freedom of action is one of the most important human features because it allows us to fulfill our desires, pursue our goals and claim moral responsibility for our actions. However, one cannot deny that many (if not all) of our actions and decisions are influenced by elements in our environment (e.g. advertising, actions of others, etc.) and are guided by our history (e.g. education, past experiences, etc.). These observations can lead to the question whether we really can control our behavior intentionally or that intentional free will is only an illusion. In philosophy this question is known as the problem of free will and has been the subject of philosophical discussions over centuries.

Because in the present thesis we focused on the ability of selecting tasks on the basis of free choice, we start this introduction with an overview of the most important perspectives in philosophy about the problem of free will (for extensive reviews see Kane, 2002; Watson, 2003).

THE PROBLEM OF FREE WILL IN PHILOSOPHY

The traditional idea about human behavior is that our actions are free and are directly caused by an intentional decision. This idea is very important in our society because it implies that people are morally responsible for their actions. Another perspective about human behavior is called *determinism*, which entails that all our actions, thoughts and feelings are determined by past events (e.g. brain processes, environment, education, etc.), which follow the laws of nature. Because in this perspective behavior can be seen as a result of an interaction between brain processes and the environment, it leads to the position that all human behavior is caused by mechanisms that can be investigated and predicted. But what does determinism imply for the existence of an intentional free will?

At first sight, determinism and intentional free will seem incompatible positions. This conviction is called *incompatibilism* and is supported by the *hard determinists*. In short, these philosophers argue that a consequence of a deterministic view is that all our actions must be caused by other events and hence that intentional free will cannot be the cause of our actions. A more thorough elaboration of this so-called *consequence argument* can be found in work of van Inwagen (1983). According to hard determinism the perception of an intentional free decision, which is the cause of our behavior, is nothing more than an illusion. However, this view has large consequences as for moral responsibility. When we only act in response to preceding events in the environment, on the basis of what is in our genes or in the way we are educated, how can we ever be held responsible for our actions?

Another group of philosophers that support incompatibilism are the *libertarians*. These philosophers reject the idea that our actions are completely determined and argue that the freedom of action lies in the fact that our behavior is undetermined and depends on chance. By assuming that our behavior depends on chance they reject the idea that our behavior is predictable. However, this view leads to another problem. How can an event that happens by chance ever represent a responsible action? In order to explain how chance events can be compatible with freedom of action, libertarians often invoke immaterial entities such as spirits, souls, etc. Hence, it is no surprise that religious people often are supporters of this perspective. A review of the most important arguments for and against this vision can be found in O'Connor (2003).

Another movement in psychology disagrees that believing in free will and believing in determinism are incompatible positions. These philosophers are called *compatibilists* and argue that the fact that our behavior can be predicted on the basis of past events does not mean that we do not have a free will (e.g. Dennett, 2003). They even put it stronger. Behavior *can* only be free when caused by other events such as emotions or brain processes. In this interpretation, free actions are *unconstrained* but are never *uncaused.* According to Dennett (2003), intentional free will in compatibilism is not the same as in the traditional view, but represents the ability of a system to anticipate positive consequences and to act to avoid undesirable consequences based on past experiences. In this perspective, a person can be held responsible for his or her actions when these actions stemmed from the person's desires and preferences formed during his or her life, which can be interpreted as a person's character according to Hume (1739). This view allows investigation of human behavior as a mechanism as well as brain processes responsible for intentional behavior.

Although we recognize that this overview of the different perspectives about the problem of free will is far from exhaustive, it was included to make a more convincing case for the idea that the perspective about free will a person supports has large consequences on how that person can investigate and interpret human behavior.

INVESTIGATING THE PROBLEM OF FREE WILL IN PSYCHOLOGY

In modern cognitive science the general idea is that our actions are caused by processes in the brain that interact with the environment.

However, the debate is still ongoing whether brain processes also can explain mental subjective phenomena such as intentional free will, consciousness, etc. (e.g. Sherrington, 1940), and whether the perception of an intentional decision indeed represents the trigger of our actions. Much of the argumentation for the illusory nature of intentional free will in cognitive science is based on a study performed by Libet, Gleason, Wright, and Pearl (1983). These authors started from the idea that when the perceived intentional decision would be the trigger of an action, the action itself and the brain activity to perform this action should occur after this feeling. In an EEG study he used an electrophysiological marker, the readiness potential, as a measure for the activation in the brain that corresponds with the initiation of an action. Surprisingly, it was found that the point in time when subjects decided to perform an action followed approximately 350 ms *after* the brain activation related to that action started to build up. This remarkable finding indicated that the brain starts doing something first, followed by the perception of an intention to do the action. Although the results of Libet et al. (1983) seem to reject the causal role of an intention in our behavior, it is worth mentioning that Libet (1999) himself did not agree with that interpretation. Libet believed that although free will may not cause behavior it can still act as a veto over automatic activity. This idea was supported by the finding that although the decision occurs 350 ms after the increase in brain activation, it still occurred 200 ms before the action really took place. Despite this veto-account of Libet (1999), the results of Libet et al. (1983) together with some other evidence brought the social psychologist Wegner (2002), amongst others, to the idea that the perception of an intentional decision in a classic view is only an illusion. Although Wegner believed that the mechanisms of our acts are deterministic in nature, he believed that the illusion of free will serves an important goal. It informs us that we are the cause of our actions, which gives us moral responsibility for them. In line with the compatibilist Dennett (2003), he also argued that intentionality lies in the ability of a system to learn more from past actions, in order to be more efficient in future behavior.

In sum, in cognitive sciences more and more evidence seems to indicate that behavior that is considered to be intentional is caused by brain processes that are non-intentional in nature. This opens the door for psychologists to investigate the psychological processes that are involved in intentional behavior; or to put it in the words of Logan (2003, p.45): '… the main job of psychology is to explain how intentionality can arise out of non-intentional stuff.'

EXECUTIVE CONTROL: INTENTIONALITY IN PSYCHOLOGY

Neuroscience studies have found that the regions involved in intentional behavior are mostly localized in the frontal lobes of the brain (e.g., Stuss & Benson, 1986). It is found that when people have a damaged frontal lobe they often show a reduced performance in so-called executive tasks such as the Wisconsin Card Sorting Test and the Tower of Hanoi (Damasio, 1994; Shallice & Burgess, 1991). These patients seem to have problems with planning of future actions and with keeping track of ongoing actions when pursuing particular goals. These lost abilities combined with damage in the frontal lobes have been called the frontal lobe syndrome, and resembles to what people would attribute intuitively to a loss of the ability to act intentionally. In psychology this control portion of the brain is called *executive control.*

Not surprisingly, this control mechanism received a lot of attention in experimental and cognitive psychology and occupied a central role in several psychological theories and models. For example, an influential psychological model that can be linked to the study of executive control is the multi-component model of working memory developed by Baddeley (1986). In this model, next to two 'slave' components of working memory that are responsible for the active maintenance of phonological information (the phonological loop) and visual and spatial information (the visuo-spatial sketchpad), a central component was incorporated to account for executive control, called the central executive. Also, in an influential model of attentional control, introduced by Norman and Shallice (1986), a similar control mechanism was included, namely the Supervisory Attentional System (SAS).

Research in the framework of these psychological models could identify a variety of psychological processes that depend on executive control, the co-called executive functions. Research showed that the most important functions of executive control are, shifting between tasks, updating working memory and inhibiting automatic actions (e.g. Logan, 2003; Miyake et al., 2000). That the study of these executive functions is very important to understand human behavior is shown by the large amount of studies investigating these processes in cognitive psychology, cognitive neuroscience, psychopathology, study of life-span development, and the study of individual differences. Undoubtedly, executive functions also play a crucial role our in daily life, especially in situations in which mental flexibility is important.

Imagine a situation in which a person is performing one task (e.g. working at a manuscript on a computer) and has to switch to another task (e.g. answering the phone that is ringing). In such a situation one can assume that this person has to activate the new task goal (e.g. answering the phone), inhibit the first task goal and update working memory with the rules (e.g. pick up the phone with right hand and bring it to your ear and mouth) needed to accomplish the new task goal. In that perspective, studying human behavior in situations in which people have to shift between tasks can provide new insight into the processes that are needed to exert executive control and the ability to perform intentional goal-directed behavior.

TASK SWITCHING PARADIGM

A first attempt to investigate the ability to shift tasks in a controlled experimental setting was done by Jersild (1927). Years later, these experiments were considered as the starting point of the *task-switching paradigm* (Spector & Biederman, 1976). In order to investigate task-switching performance, Jersild compared the duration of blocks of trials in which subjects switched tasks constantly with the duration of blocks in which subjects repeated the same task from trial to trial. By doing this, he was the first to observe the switch cost. He observed that, on an average, the switch trials were performed much slower and less accurate than the repetition trials. This switch cost was considered as a measure of the duration of the executive processes that are needed when subjects are switching between tasks. In later studies the original procedure of Jersild (1927) was adjusted because it was assumed that in the blocks of trials with only task repetitions only one task had to be maintained in working memory while in the switch blocks two tasks had to be maintained. This difference results in greater effort and arousal in task switches compared with task repetitions and leads to an overestimation of the switch cost. This confound was eliminated in a study of Rogers and Monsell (1995) where the alternating-runs procedure was introduced. In this procedure subjects had to switch tasks in a predictable fashion every *N* trials, with *N* being constant, allowing comparison of switch and repetition trials within a single block. This resulted in a more valid measure of the executive processes.

Another finding in the task-switching paradigm is that the switch cost is larger with short than with long inter-trial intervals (ITIs). At first sight this reduction in switch cost indicates that time consuming executive processes that cause the switch cost can be prepared with a long ITI, causing faster switch trials (e.g. Rogers & Monsell, 1995). However, Altmann (2004a; 2004b) found that this reduction in switch cost only occurs when ITI is varied within subjects but not when varied across subjects. The finding that the switch cost can depend on the used design (within- and between-subjects design) suggests that executive processes involved in a task switch seem to be a functional rather than a structural property of shifting between tasks (e.g. Poulton, 1982). In addition, it was also found that the size of the switch cost in the alternating runs procedure was not only caused by worse performance on task switches but also by better performance due to task-set priming on the task repetitions. This point was illustrated by Allport, Styles and Hsieh (1994) in a situation in which subjects were told to switch between a highly practiced (word reading) and a less practiced task (color naming) on Stroop stimuli. Surprisingly, it was found that switching to the easier task produces a larger cost than switching to the more difficult task. This asymmetric switch cost supports the idea that the switch cost partly represents persisting activation of tasks, and thus again not solely the time taken by executive processes needed to switch tasks.

In order to control the effects of task-set priming, Meiran (1996) suggested using a task-cuing procedure, which was previously introduced by Sudevan and Taylor (1987). In this procedure the task sequence was unpredictable and on every trial a cue was presented to inform the subjects which task they had to perform. The introduction of this cue was advantageous because it allowed independent manipulation of the cue-stimulus interval (for the manipulation of the efficiency of executive processes needed on a task switch) and the response-cue interval (for the manipulation of the impact of task-set priming). Indeed, with this procedure, it was found that with a sufficiently long response-cue interval and with a short cue-stimulus interval, task-set priming was almost eliminated and the switch cost represented a better measurement of the time needed by executive processes to switch tasks (Meiran, 1996).

However, again, this task-cuing procedure did not offer a solution to the problem of the validity of the switch cost measurement. By using two different cues per task, Logan and Bundesen (2003) and Mayr and Kliegl (2003) observed almost simultaneously that a large part of the switch cost in the task-cuing procedure was caused by shorter cue-encoding processes on task repetitions when the cue was repeated. These results suggest that earlier reported task-switch costs measured with one cue per task are contaminated with cue-related processes. The observation that cues can activate tasks automatically without the need for executive processes can be considered as a major problem when one attempts to use the task-cuing procedure as a tool to investigate executive control.

In our opinion, all these findings above point to a more general problem with the task-switching paradigm. Namely, a task a subject has to perform is always imposed by the experimenter and is never selected by the subject. In other words, control on which behavior to perform is taken away from the subject and is delegated explicitly to the environment. In this perspective one could even argue that no true intentional control can be measured in the task-switching paradigm.

VOLUNTARY TASK SWITCHING

In an attempt to capture true intentional control in a task-switching context, Arrington and Logan (2004) introduced a new procedure. In this new procedure, the tasks were not cued nor performed in a predictable order, but subjects had a free task choice on each trial. Because in this voluntary task switching (VTS) procedure subjects have full control about which task they perform, this procedure can be considered to have a higher ecological validity for the study of intentional control than the traditional procedures. Arrington and Logan (2004; 2005) observed that, even when subjects are selecting tasks voluntarily, task switches still show a cost compared to task repetitions.

In a study of Liefooghe, Demanet and Vandierendonck (2009) was found that the reduction in switch cost was identical when the ITI was varied within and between subjects, supporting the idea that the switch cost obtained with VTS really is a structural cost. A follow-up study of Liefooghe, Demanet and Vandierendonck (in press) investigated whether persisting activation of a previously executed task can influence the switch cost in VTS. Based on the idea that the switch cost in VTS is a pure measure of executive processes, it was predicted that the persisting task activation would have no effect on the switch cost in VTS. In order to investigate the influence of persisting task activations, subjects were asked to switch voluntarily between a word-reading task and a color-naming task on Stroop stimuli, similar as in the study of Allport et al. (1994) described above. The observation that the asymmetric switch cost was very small in VTS in comparison with other procedures again supports the idea that the switch cost in VTS represents executive control.

Also on a neuro-anatomical level, differences were observed between cued and voluntary task switching. In a study using functional magnetic resonance imaging, Forstmann, Brass, Koch, and von Cramon (2006) revealed stronger fronto-medial activation in VTS compared to cued task switching. More specifically, voluntary task choices resulted in a stronger activation in the left middle cingulate cortex than a cued task choice. This is a region that has been shown to be involved in response-selection processes (e.g. Lau, Rogers, Ramnani, & Passingham, 2004). This activation was suggested to be responsible for the voluntary choice of the task set. In a follow-up study this frontal activation in VTS was replicated using EEGs (Forstmann, Ridderinckhof, Kaiser, & Bledowski, 2007). The involvement of the fronto-medial cortex in VTS was confirmed in a study by Haynes et al. (2007) where was shown that internally driven task choices could be best predicted from activation in the anterior medial prefrontal cortex.

Another advantage of the VTS procedure is that one cannot only measure how fast or how accurate subjects are performing a task, but also how many times and when they choose to perform a particular task. The availability of information about the task choice allows studying intentional control in task switching in a totally new perspective. The idea that different kinds of control may exist in intentional behavior is not new. The distinction between task choice and task execution may be related to the distinction made by Searle (1983) between a ‘prior intention’ to act (the conscious desire to do something) and an ‘intention in action’ (steps that need to precede an executed act). Support for this distinction in VTS was already reported in a study of Arrington and Yates (2009). These authors found that the switch cost and task choice are tapping on different underlying processes by observing that both are correlating with different attentional networks as measured by the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002).

Investigating this task choice, Arrington and Logan (2004; 2005) observed that when subjects have to choose among two tasks and when they are instructed to select tasks in a random order, they show a tendency to repeat tasks more than to switch between tasks. This so-called task-repetition bias was found to be stronger on short than long ITIs. Arrington and Logan (2005) suggested that this task-repetition bias results from a competition between two executive processes, one process related to the random task generation (e.g. Baddeley, Emslie, Kolodny, & Duncan, 1998) and the other related to switching tasks. On short ITIs this competition would be more severe. Arrington and Logan (2005) also observed that task choice is largely unaffected by elements in the environment, which supports the claim that a task choice is made on the basis of internal selection processes. Mayr and Bell (2006) replicated the task-repetition bias and on the basis of a correlational analysis they concluded that subjects with slower task repetitions switched more between tasks. According to these authors this finding suggests that subjects who treat trials as discrete events by strategically inhibiting the preceding task set, repeat tasks less often. They also argued that subjects have a natural tendency to repeat the tasks, which is caused by the fact that the previous task is the most active one when selecting a new task. In other words, Mayr and Bell (2006) interpreted the repetition bias as the result of the efficiency of executive processes to avoid sticking with the currently most active task-set. As an underlying executive process they proposed an active inhibition of the preceding task set. In another study, Lien and Ruthruff (2008) found evidence for the involvement of task-set inhibition when selecting tasks voluntarily. Using three tasks, they observed that subjects avoided switching back to a task that was recently abandoned. They attributed this effect to backward inhibition (Mayr & Keele, 2000), which entails that in order to implement a new task set, the previous task set must be inhibited. Lien and Ruthruff (2008) argued that this inhibition persists to the next trial and causes subjects to avoid switching back to the recently abandoned task.

Recently, an EEG study performed by Vandamme, Szmalec, Liefooghe and Vandierendonck (in press) provided direct evidence for the idea that subjects have a natural tendency to repeat tasks and that this tendency has to be counteracted for a task switch to be successful. By using an experiment in which two tasks were mapped onto different hands, lateralized readiness potentials (LRPs) were used to investigate the time course of the task-selection mechanisms. On switch trials, the previously activated hand (task) was activated again, as shown by a foreperiod LRP, followed by a switch in activation to the alternative hand, shown by a late LRP. This suggests that subjects indeed activate the preceding task again in an early selection stage and that when one decides to switch this tendency is counteracted.

In contrast with Arrington and Logan (2005), Mayr and Bell (2006) observed that in particular situations elements in the environment can have a strong impact on the task choice. They observed that when the stimulus was repeated, the chance to repeat the task was higher than when the stimulus was alternated. They also found that this stimulus-repetition effect was reduced when subjects treated trials as discrete events. From the observation that elements of the environment can bias the task choice, Mayr and Bell (2006) concluded that the VTS procedure cannot only be used to study intentional control but also to study exactly those factors that stand in the way of intentional control.

In line with this conclusion, recently a series of studies were conducted in which various factors were discovered that can bias a voluntary task choice. Weaver and Arrington (in press) observed that items held in working memory can affect task choice and Arrington and Rhodes (in press) observed that task choice can be influenced by the perceptual characteristics of the stimulus. Stimuli that were presented in the left visual field were more likely to engage a global categorization task, while stimuli presented in the right visual field were more likely to engage a local categorization task. Arrington (2008) could show that stimuli can bias task choice when two tasks with univalent stimuli are used and a stimulus of one task is earlier available than the other. She also observed that this effect was stronger with short than with long ITIs. Based on these findings, Arrington (2008) suggested to conceptualize task choice in VTS as a race between the activation of tasks guided by the exogenous factors (bottom-up control) and the activation of tasks guided by endogenous executive processes (top-down control). This suggests that when ample time is provided for top-down control to activate a task, this task activation will reach the selection threshold first, eliminating all effects of bottom-up control. However, when top-down control is hampered by time constraints and bottom-up control activates a task strongly, this automatic activation will reach the selection threshold first and bottom-up control will define a task selection.

RESEARCH GOALS AND OVERVIEW OF THE PRESENT THESIS

The main goal of the present thesis was to investigate the interplay between top-down and bottom-up control when selecting tasks in the VTS procedure. By introducing different sources of bottom-up control and by manipulating the efficiency of top-down control, we tried to learn more about that the mechanisms underlying intentional goal-directed behavior. Besides this Introduction (*Chapter 1*) and the General Discussion (*Chapter 6*), there are four empirical chapters in this thesis. Each chapter was written as an individual paper. We will now give a short outline of the chapters.

In *Chapter 2*, we investigated how stimuli can guide a task choice in VTS. In a first experiment we tried to replicate the stimulus-repetition effect observed by Mayr and Bell (2006). In a second experiment we investigated the impact of task-irrelevant stimulus features on the task choice. In a third experiment we investigated if stimuli that are associated with a particular task can trigger the selection of that task. In order to manipulate the efficiency of top-down control a concurrent working memory load was used in all these experiments. By manipulating the efficiency of top-down control we tried to investigate how top-down control interacts with different bottom-up factors.

In *Chapter 3*, we tested three accounts about voluntary task selection that were proposed in *Chapter 2*. First, we tested the account that the observed task-repetition bias is related to the fact that tasks had to be selected. Second, we tested the account that the higher task-repetition bias with a concurrent working memory load in *Chapter 2* is related to a reduced ability to switch between tasks under load. Third, we tested the account that the stimulus-repetition effect observed in *Chapter* 2 is caused by the associations that are formed between a stimulus and a response during task execution. In order to investigate these accounts, subjects were not asked to select tasks but to select hands randomly.

Chapter 4 was designed to investigate the hypothesis that a procedure in which a separate task selection and task execution response are given, provides a good measure of voluntary task choice uncontaminated by bottom-up influences. In this chapter we investigated that by using two responses per trial, new response-sequence effects on task selection are induced that are non-existing in single-registration procedures. In order to manipulate the efficiency of top-down control, the length of the preparation interval was varied.

In *Chapter 5*, a model for voluntary task selection was introduced, in which is assumed that task selection is based on automatic retrieval of chains of task information from long term memory. In this model a) the requirement to produce random sequences, b) the idea that the ease of execution are taken into account and c) the possibility that bottom-up factors can bias task choices, were incorporated. The fits of the predictions of this chain-retrieval model were compared with the fits of alternative models that are typically used to predict random selection behavior. Additionally, several tests were performed to investigate the importance of the three parameters of the model.

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CHAPTER 2
VOLUNTARY TASK SWITCHING UNDER LOAD: CONTRIBUTION OF TOP-DOWN AND BOTTOM-UP FACTORS IN GOAL-DIRECTED BEHAVIOR

Psychonomic Bulletin & Review (in press) [1]

The present study investigated the relative contribution of bottom-up and top-down control to task selection in the voluntary task switching (VTS) procedure. In order to manipulate the efficiency of top-down control, a concurrent working-memory load was imposed during VTS. In three experiments bottom-up factors such as stimulus repetitions, repetition of irrelevant information and stimulus-task associations were introduced to investigate their influence on task selection. We observed that the tendency to repeat tasks was stronger under load, suggesting that top-down control counteracts the automatic tendency to repeat tasks. The results also indicated that task selection can be guided by several elements in the environment, but that only the influence of stimulus repetitions depend on the efficiency of top-down control. The theoretical implications of these findings are discussed within the interplay between top-down and bottom-up control that underlies the voluntary selection of tasks.

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[1] This paper was co-authored by Frederick Verbruggen, Baptist Liefooghe and André Vandierendonck.

INTRODUCTION

Many researchers assume that goal-directed behavior relies on the intentional and controlled activation of task goals (Baddeley, 1992; Logan & Gordon, 2001; Miller & Cohen, 2001). However, several studies demonstrated that task goals can also be activated automatically by information in the environment (e.g. Mattler, 2003; Mayr & Bryck, 2007; Verbruggen & Logan, 2009) or by the retrieval of previously formed associations between a stimulus and a particular goal (e.g. Verbruggen & Logan, 2008; Waszak, Hommel & Allport, 2003). In the present study we examined the contribution of top-down and bottom-up activation of task goals in voluntary task switching (VTS).

In VTS, subjects switch between cognitive tasks. They are free to select the task to perform, as long as each task is selected an approximate equal number of times and subjects do not follow a predictable pattern of task selections (Arrington, 2008; Arrington & Logan, 2004; 2005; Liefooghe, Demanet, & Vandierendonck, 2009; Mayr & Bell, 2006). A general finding is that subjects repeat tasks more often than they switch (Arrington & Logan, 2005). This task-repetition bias has been linked to the efficiency of top-down control processes involved in the voluntary selection of task goals. For example, Mayr and Bell (2006) argued that subjects tend to repeat tasks because the task of the previous trial is still the most active one when selecting a new task. In order to overcome this bias, the activated task has to be inhibited. Thus, selection of tasks would depend on top-down control processes (see also Arrington & Logan, 2004, 2005).

However, several studies showed that bottom-up processes also contribute to task selection in VTS (e.g. Arrington, 2008) and Mayr and Bell (2006) observed that the task-repetition bias was stronger when the stimulus of the previous trial was repeated compared to when the stimulus alternated. This stimulus-repetition effect suggests that voluntary task selection is not completely immune to bottom-up priming effects.

In the present study, we focused on the contribution of top-down control and bottom-up priming in voluntary task selection. Studies in several paradigms have shown that bottom-up factors contribute more to behavior in cognitively demanding situations (see Lavie, 2005 for a review). A manipulation that is often used to reduce the efficiency of top-down control is a concurrent working memory (WM) load (e.g. Logan, 2007). To test the relative contribution of bottom-up and top-down processes in task selection, we manipulated WM load in the VTS procedure in three experiments. Each experiment consisted of two conditions: a load condition and a no-load condition (see Logan, 2007). In the *load condition*, subjects were shown six letters which they had to remember (*study phase*), followed by 13 voluntary switch trials (*VTS phase*), followed by a *recall phase* in which subjects had to indicate which letters were shown in the study phase. In the *no-load condition*, the study phase was immediately followed by the recall phase, which was in turn followed by the VTS phase, so that there was no concurrent memory load during the test phase. We predicted that bottom-up control would contribute more to task selection in the load condition than in the no-load condition. The results of Experiment 1 confirmed this prediction and showed that the stimulus-repetition effects and the task-repetition bias were stronger in the load condition than in the no-load condition. In Experiments 2 and 3, we further tested how stimulus repetitions affected task-selection processes. We propose three accounts for the stimulus-repetition effect. First, the effect could be caused by the repetition of visual information on the screen; this could prime the decision to repeat the task (see also Arrington & Logan, 2005). Second, the effect could be caused by retrieval of associations that were formed between the stimulus and the task executed on the previous trial. When the stimulus repeats, this association is retrieved and the task goal of the previous trial is primed (see e.g. Verbruggen & Logan, 2008). Third, the effect could also be due to the retrieval of associations between the stimulus and the task-execution response (see e.g. Hommel, 1998; Soetens, 1998). When the stimulus repeats, the task-execution response of the previous trial is also repeated.

This would suggest that subjects did not select a new task first; instead, they would have directly executed a response. Experiments 2 and 3 were designed to test these accounts by including repetitions of task-irrelevant features in Experiment 2 and by the formation of strong stimulus-task associations in a training phase in Experiment 3.

EXPERIMENTS

Because the method and results sections of the three experiments strongly overlapped, we describe them together.

METHOD

Subjects and materials. 80 students from Ghent University participated for course requirements and credit (Exp.1: 24; Exp.2: 24: Exp.3: 32). They were tested individually by means of a Pentium III personal computer with a 17-inch color monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). We used an external response box with 4 buttons to register responses in the VTS phase and a QWERTY keyboard to register responses in the recall phase.

Procedure. The experimental session of Experiment 1 consisted of a study phase, a recall phase, and a VTS phase. In the study phase we presented six different low inter-confusable consonants (see Vandierendonck, De Vooght, & Van der Goten, 1998 for details). The consonants were presented in the center of the screen at a rate of one item per second (500 ms on; 500 ms off). In the recall phase subjects had to recall the memorized items in the correct order by typing the items on the keyboard. There were no time constraints in the recall phase. In the VTS phase subjects categorized a stimulus as smaller or larger than ‘5’ (magnitude task) or as odd or even (parity task). We used digits 1-9, excluding 5. The magnitude task (smaller: left-outer button; larger: left-inner button) and the parity task (odd: right-inner button; even: right-outer button) were mapped on a different hand. The task-to-hand assignment was counterbalanced across subjects. There were 13 trials in the VTS phase. Each trial started with the presentation of a stimulus. When a response was executed or the maximal response time of 3000ms had elapsed, a fixed response-stimulus interval of 100 ms started. The first trial was a filler; of the remaining 12 trials four were stimulus repetitions (25%). The experimental session started with three practice blocks in which subjects practiced a) the study and recall phase separately, b) the VTS phase separately and c) the combination of the three phases. Before the practice blocks, we presented the instructions of Arrington and Logan (2004) (in Dutch) on the screen and paraphrased them if necessary. The practice trials were followed by the experimental session, which consisted of 20 lists per condition (load condition: study-test-recall, or no-load condition: study-recall-test). The order of the conditions was counterbalanced over subjects. The experimental session lasted approximately 30 minutes.

Experiment 2 was identical to Experiment 1 except that in the VTS phase, stimulus repetitions were excluded. Instead, we presented a task-irrelevant shape on each trial. The target stimulus appeared inside one of four white non-filled shapes (circle, triangle, hexagon, square; each shape = 5.9cm^2). On 25% of the trials, the shape of the previous trial was repeated.

In Experiment 3, subjects performed an ‘animacy’ task (‘non-living’ or ‘living’), or a ‘size task’ (‘smaller’ or ‘larger than a basketball’) on nouns. 128 nouns were selected on the basis of word frequency (per million) and word length (average frequency: 11.0; average length: 5.6). For every subject, three different stimulus sets of 32 nouns were selected (matched for frequency and word length). All sets consisted of 8 large living, 8 small living, 8 large nonliving, and 8 small nonliving stimuli. Before the experimental session, subjects performed a training session of 16 single-task blocks (±40 minutes). In the training session, the first stimulus set was always used for the animacy task; the second stimulus set was always used for the size task. Subjects practiced one task in the odd-numbered blocks and the other task in the even-numbered blocks. Task-to-block mapping was counterbalanced. Each training block consisted of 32 trials, and each item of the relevant set was presented once. All trials in the training session started with the presentation of a noun in the center of the screen. This stimulus remained on the screen for 1,000 ms, regardless of the response time. The maximal-response time was 4,000 ms and the response-stimulus interval 750ms. Subjects responded orally by saying '[bu:]' for living, '[bi:]' for non-living, '[ba:]' for small, and '[bo:]' for large. The structure of the experimental phase of Experiment 3 was similar to that of Experiment 1. Because VTS stimuli were words, the WM load consisted of six different numbers (range 1-9). There were no other differences in the study or recall phase. In the VTS phase the animacy task was performed with one hand (non-living: left-outer button; living: left-inner button) and the size task with the other hand (small: right-inner button; large: right-outer button). Eight lists of VTS trials were used in both load conditions. In each VTS phase, twelve stimuli were presented: four stimuli of the 'animacy' set, four stimuli of the 'size' set, and four stimuli of the third stimulus set (the neutral set, which was not used in the training phase). The maximal response time in the VTS trials was 5,000ms because the tasks were more difficult than in Experiments 1 and 2.

RESULTS AND DISCUSSION

The first trial of each VTS phase and trials following an error were discarded (data loss: Exp1 = 12.8%; Exp2 = 11.5%; Exp3 = 12.3%). In this study, we are interested in the processes that are involved in the voluntary selection of tasks. Therefore, in the results section, we will focus on task-choice data only. Analyses of response latencies are presented in Appendix A. The task-selection proportions appear in Table 1 and all analyses appear in Table 2.

Table 1: Task-repetition proportions as a function of load, trial type and task transition for Experiment 1 and 2 and task-selection proportions as a function of load, trial type and task for Experiment 3.

	no-load condition		***load condition***	
	task repetitions	*task switches*	*task repetitions*	*task switches*
Experiment 1				
stimulus repetitions	.48 (.04)	.52 (.04)	.62 (.04)	.38 (.04)
stimulus alternations	.48 (.02)	.52 (.02)	.54 (.02)	.46 (.02)
Experiment 2				
shape repetitions	.55 (.02)	.45 (.02)	.59 (.03)	.41 (.03)
shape alternations	.51 (.03)	.49 (.03)	.55 (.02)	.45 (.02)
	animacy task	*size task*	*animacy task*	*size task*
Experiment 3				
animacy stimuli	.54 (.02)	.46 (.02)	.57 (.02)	.43 (.02)
size stimuli	.46 (.02)	.54 (.02)	.46 (.02)	.54 (.02)
neutral stimuli	.51 (.02)	.49 (.02)	.49 (.01)	.51 (.01)

Note – Standard errors are presented within brackets.

Table 2: Outcome of the ANOVAs conducted on the selection proportions of task repetitions for Experiments 1 and 2, and of the task-selection proportions for Experiment 3.

		Experiment 1		
		Proportion task repetitions		
	MSe	*(df1,df2)*	*F*	η_p^2
load	.0118	(1,23)	18.70*	.45
trial type	.0254	(1,23)	1.41	.06
load*trial type	.0034	(1,23)	12.96*	.36
		Experiment 2		
		Proportion task repetitions		
	MSe	*(df1,df2)*	*F*	η_p^2
load	.0045	(1,23)	7.46*	.24
trial type	.0027	(1,23)	10.84*	.32
load*trial type	.0025	(1,23)	.00	.00
		Experiment 3		
		Proportions ‘animacy’ task		
	Wilks	*(df1,df2)*	*F*	η_p^2
load	.9986	(1,31)	.04	.00
trial type	.5204	(2,30)	13.83*	.48
load*trial type	.9390	(2,30)	.98	.06

Note – *: $p<.05$

Data of Experiment 1 were analyzed by means of a repeated measures ANOVA with load (no-load vs. load) and trial type (stimulus repetition vs. alternation) as factors, performed on the task-repetition proportions. When relevant, individual *t*-tests were performed to test whether proportions were different from .50. As shown in Tables 1 and 2 subjects repeated the task of the previous trial more often in the load (*M*=.579, *SE*=.029; comparison .50: *t*(23) = 2.68, *p* = .01) than in the no-load condition (*M*=.483, *SE*=.026; comparison .50: *t*(23) = -.66, *p* = .51). These results confirm the hypothesis that top-down control is needed to counteract the tendency to repeat tasks (e.g. Mayr & Bell, 2006). The absence of a tendency (in comparison with .50) to repeat tasks in the no-load condition is probably due to the length of the sequences. This result converges with the findings of Rapoport and Budescu (1997) indicating that in random selection of events there is a larger tendency to alternate for shorter sequences.

Importantly, we observed a stimulus-repetition effect in the load but not in the no-load condition of Experiment 1 (see Tables 1 and 2). Simple main effects showed that the effect of trial type was significant in the load, $F(1,23) = 4.93$, $MSE = .0163$, $\eta_p^2 = .18$, but not in the no-load condition, $F<1$. This suggests that bottom-up control contributes more to task selection in cognitively demanding situations (i.e. the load condition) than in less demanding situations (i.e. the no-load condition). The complete absence of a stimulus-repetition effect in the no-load condition is probably due to the relatively low number of stimulus repetitions (see also Arrington & Logan, 2005, Experiments 3 and 4).

Data of Experiment 2 were analyzed by means of a repeated measures ANOVA with load (no-loaded vs. load) and trial type (shape repetition vs. alternation) as factors. The analyses showed that tasks were repeated more often in the load (*M*=.570, *SE*=.024; comparison .50: *t*(23) = 2.91, *p* = .01) than in the no-load condition (*M*=.532, *SE*=.023; comparison .50: *t*(23) = 1.41, *p* = .17). Furthermore, tasks were repeated more often on shape repetitions (*M*=.569, *SE*=.022) than on shape alternations (*M*=.534, *SE*=.024), which suggests that repeating visual information can prime task repetitions. However, the size of the shape-repetition effect was comparable for the load and the no-load condition (see Table 2). The absence of an interaction suggests that the stimulus-repetition effect observed in Experiment 1 was not simply caused by the repetition of visual information on the screen.

The data of Experiment 3 were analyzed in two steps. First, we examined whether task selections were influenced by the training phase by means of a repeated measures ANOVA with load and stimulus set (animacy vs. size vs. neutral set) as factors. We focused on the proportions of the animacy task; we would get symmetrical results if the focus was on the size task. The analysis showed that there was a strong learning effect (see Table 2). Contrasts showed that the animacy task was selected more often for the animacy set (*M*=.554, *SE*=.012) than for the neutral set (*M*=.501, *SE*=.010), *F*(1,31)=10.31, *MSE*=.0088 , η_p^2= .25, and the size set (*M*=.458, *SE*=.011), *F*(1,31)=28.57, *MSE*=.0104, η_p^2= .48. The difference between the size and neutral sets was also significant, *F*(1,31)=7.94, *MSE*=.0074, η_p^2= .20, which suggests that subjects tended to choose the size task for the size set. Combined, these findings suggest that learned stimuli primed the selection of the task they were associated with in the training phase. However, this stimulus-priming effect was similar in the no-load and load condition (Table 2). The absence of an interaction shows that stimulus-task associations do not cause the priming effect in Experiment 1.

In a second step, we examined whether there was an influence of load on the general task-repetition bias, like in the other experiments. We analyzed task-repetition proportions with a one-way ANOVA with load as factor. Consistent with Experiments 1 and 2, we found that tasks were repeated more often in the load (*M*=.517, *SE*=.021; comparison .50: *t*(32) = .81, *p* = .42) than in the no-load condition (*M*=.472, *SE*=.020; comparison .50: *t*(32) = -1.44, *p* = .16), *F*(1,31)=6.55, *MSE*=.0050, η_p^2= .17. Again, this finding shows that the task-repetition bias is stronger in cognitively demanding situations.

Recall phase. The proportions of correct recall represent the probability that a particular item was remembered correctly in the correct order. We analyzed the proportions by means of a simple main effects ANOVA with load as the only factor. As shown in Table 3, proportions were higher in the no-load than in the load condition, which can be explained by the different order of the VTS and recall phases.

Table 3: Mean proportions of correct recall in the no-load and load condition and the results of the main effect ANOVAs on these proportions with load as the only factor.

	no-load	load	main effect load			
			(df1,df2)	*F*	*MSe*	η_p^2
Experiment 1	.93 (0.1)	.84 (0.2)	(1,23)	42.80*	.0025	.65
Experiment 2	.91 (0.1)	.84 (0.2)	(1,23)	31.74*	.0020	.58
Experiment 3	.97 (0.1)	.83 (0.3)	(1,31)	27.36*	.0101	.47

Note – *: $p<.05$. Standard errors are presented within brackets.

CONCLUSION

In the present study, we examined how bottom-up and top-down processes contribute to voluntary selection of tasks in situations that are cognitively demanding. In Experiment 1, we found that subjects repeated tasks more often in the load (demanding) condition than in the no-load (non-demanding) condition. We replicated this load effect in Experiments 2 and 3. The effect of load on the task-repetition bias is consistent with the idea that top-down processes are required to overcome the tendency to keep repeating the same task. This is consistent with the idea that top-down control inhibits the most recent task, which reduces the tendency to repeat tasks (Mayr & Bell, 2006; see also Lien & Ruthruff, 2008).

In Experiment 1, we found that stimulus repetitions elicited more task repetitions in the load than in the no-load condition. This observation seems to support the idea that bottom-up control contributes more to task selection in cognitively demanding situations (for a similar idea; Arrington, 2008; Lavie, 2005). In Experiments 2 and 3, however, we observed priming effects of repeating shapes and acquired stimulus-task associations but these effects did not interact with load. This suggests that some bottom-up driven effects occur independently of the cognitive demands of the situation. Furthermore, the results of Experiments 2 and 3 suggest that the stimulus-repetition effect, which was observed in Experiment 1 and which interacted with load, was not caused by repetition of visual information or the retrieval of stimulus-task associations. Instead, we propose that the stimulus-repetition effect is caused by the retrieval of associations between the stimulus and the task-execution response. When the stimulus is repeated, the task-execution response of the previous trial is activated and executed again. Interestingly, this suggests that on a proportion of the trials, a response is executed without advance selection of a new task. The interaction with load in Experiment 1 suggests that there are more non-selection trials when top-down control is degraded in highly demanding situations. In less demanding situations, however, top-down processes can counteract this response-repetition tendency. This seems to suggest that an important function of top-down control in VTS is to protect task-selection from automatically triggered responses. This function of top-down control can be related to the response-inhibition account of Hübner and Druey (2006), which states that in a task-switching context a response has to be inhibited in order to avoid its automatic re-execution on the following trial (for a similar idea, Logan & Gordon, 2001). In this perspective, the present study contributes by showing that when a response is inhibited less efficiently in a high demanding situation, the chance to re-execute this response on the next trial is increased on stimulus repetitions. In sum, this study showed that different bottom-up factors can guide task selection but also that top-down control is necessary to shield task selection from the effects of stimulus-response associations, and to counteract the tendency to perseverate tasks.

In conclusion, the data of the present study also allowed us to formulate an answer to the question what is really ‘voluntary’ or ‘intentional’ in the VTS procedure. We obtained convincing evidence for the ideas that task goals are automatically triggered by factors in the environment (e.g. Waszak et al., 2003) but also that subjects can inhibit recently activated task goals and suppress automatically triggered responses to protect intentional goal-directed behavior. Thus, maybe the intentional or voluntary act in VTS is not to activate what is ‘willed’ but to suppress what is ‘unwilled’.

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APPENDIX

The mean RTs and analyses are presented in Tables A1 and A2. Error rates were very low (Exp1 = 3.6%; Exp2 = 3.1%; Exp3 = 4.6%) and not further analyzed.

We analyzed the mean RTs of Experiments 1 and 2 with a repeated measures ANOVA with the factors load (no-load vs. load), trial type and task transition (task repetition vs. task switch). In both experiments, we found main effects of load [RT(no-load) < RT(load)] and task transition [RT(repetition) < RT(switch)]. The main effect of trial type was also significant, indicating that repetitions of stimuli or shapes induced faster responses than alternations. In Experiment 1, the interaction between trial type and task transition was reliable indicating that the switch cost was smaller on stimulus repetitions than alternations (see Allport & Wylie, 2000). The interaction between load and task transition was significant, indicating that the switch cost was smaller in the load than in the no-load condition. A contrast showed that this was especially due to marginally slower task repetitions in the load than in the no-load condition, $F(1,23)=3.75$, $MSE=9861$, $\eta_p^2= .14$, and not by faster switches, $F<1$ (for similar results Liefooghe et al., 2005). In Experiment 2, the interaction between load and task transition was not significant. Possibly this difference between Experiment 1 and 2 is due to the inclusion of stimulus repetitions in Experiment 1.

We analyzed mean RTs of Experiment 3 with a mixed ANOVA with the factors load, trial type (animacy vs. size vs. neutral stimulus set), task transition and task We found main effects of load [RT(no-load) < RT(load)] and task transition [RT(repetition) < RT(switch)]. Also, the main effect of trial type was significant. Contrasts showed that responses to neutral stimuli were slower than responses to stimuli of the size stimulus set, $F(1,31)=17.12$, $MSE=18931$, $\eta_p^2= .36$. The differences between neutral and animacy and the differences between animacy and size were not significant; $F(1,31)=1.61$, $MSE=34019$, $\eta_p^2= .05$, and $F(1,31)=2.64$, $MSE=42558$, $\eta_p^2=$

.08, respectively. The interaction between trial type and task was significant, indicating that performing task on a stimulus that is associated with that same task leads to better performance than performing another task. Contrasts confirmed this for both the animacy, $F(1,31)=18.19$, $MSE=39806$, $\eta_p^2= .37$, and size stimulus set, $F(1,31)=17.43$, $MSE=21759$, $\eta_p^2= .36$, but not for the neutral stimulus set, $F<1$.

Table 1A: Mean RTs as a function of load, trial type and task transition for Experiment 1 and 2 and mean RTs as a function of load, trial type and task transition and task for Experiment 3.

	no-load condition		***load condition***	
Exp. 1	*task repetitions*	*task switches*	*task repetitions*	*task switches*
stimulus repetition	624 (31)	889 (29)	656 (32)	849 (33)
stimulus alternation	831 (25)	940 (27)	877 (33)	965 (34)
Exp. 2				
shape repetition	798 (35)	930 (45)	796 (31)	989 (39)
shape alternation	809 (41)	962 (46)	837 (35)	1010 (42)

	no-load condition				***load condition***			
Exp. 3	*repetitions*		*switches*		*repetitions*		*switches*	
	animacy task	*size task*	*animacy task*	*size task*	*animacy task*	*size task*	*animacy task*	*size task*
animacy stimuli	974 (52)	1063 (62)	1155 (52)	1233 (62)	1000 (52)	1165 (68)	1233 (55)	1327 (77)
size stimuli	1042 (58)	1006 (62)	1145 (46)	1091 (39)	1138 (63)	1066 (50)	1286 (59)	1140 (55)
neutral stimuli	1054 (59)	1112 (69)	1228 (54)	1177 (43)	1097 (58)	1137 (53)	1244 (51)	1267 (59)

Note – Mean RTs and standard errors are given in milliseconds. Standard errors are presented within brackets.

Table 2A: Outcome of the ANOVAs conducted on the RTs for Experiments 1, 2 and 3.

Experiment 1

	MSe	*(df1,df2)*	*F*	η_p^2
load	16665	(1,23)	.72	.03
trial type	16818	(1,23)	63.04*	.73
task transition	30245	(1,23)	42.59*	.65
load*trial type	8087	(1,23)	2.31	.09
load*task trans	5549	(1,23)	4.76*	.17
trial type*task trans	7083	(1,23)	28.73*	.56
load*trial type*task trans	3836	(1,23)	2.00	.08

Experiment 2

	MSe	*(df1,df2)*	*F*	η_p^2
load	31502	(1,23)	1.67	.07
trial type	4213	(1,23)	7.89*	.26
task transition	15822	(1,23)	80.79*	.78
load*trial type	1901	(1,23)	.55	.02
load*task trans	4970	(1,23)	3.88	.14
trial type*task trans	4059	(1,23)	.00	.00
load*trial type*task trans	2700	(1,23)	1.89	.08

Experiment 3

	Wilks	*(df1,df2)*	*F*	η_p^2
load	.8501	(1,31)	5.47*	.15
trial type	.6417	(2,30)	8.37*	.36
task transition	.4100	(1,31)	44.60*	.59
task	.9712	(1,31)	0.92	.03
load*trial type	.9387	(2,30)	0.98	.06
load*task trans	.9878	(1,31)	0.38	.01
trial type*trans	.8244	(2,30)	3.20	.18
load*task	.9997	(1,31)	0.01	.00
trial type*task	.4647	(2,30)	17.28*	.54
task trans*task	.8849	(1,31)	4.03	.12
load*trial type*task trans	.9999	(2,30)	0.00	.00
load*trial type*task	.8751	(2,30)	2.14	.12
load*task trans*task	.9992	(1,31)	0.03	.00
trial type*task trans*task	.9959	(2,30)	0.06	.00
4-way interaction	.8699	(2,30)	2.24	.13

Note – *: p<.05

CHAPTER 3
VOLUNTARY TASK SELECTION VERSUS RANDOM HAND SELECTION

***Manuscript in preparation*[1]**

In the present study we tested the hypotheses that the task-repetition bias in voluntary task switching (VTS) is related to the fact that it is easier to repeat tasks than to switch between tasks (e.g. Arrington & Logan, 2005; Mayr & Bell, 2006) and that the effect of a concurrent working memory (WM) load on the repetition bias is related to a reduced ability to overrule task repetitions under load (Demanet, Verbruggen, Liefooghe, & Vandierendonck, in press). In two experiments, were no tasks but hands had to be selected randomly, we found support for both hypotheses by observing a tendency to alternate hands (in contrast with a tendency to repeat tasks) and by observing that a WM load did not affect the hand-selection proportions (in contrast with task-selection proportions). The finding that stimulus repetitions only affected the amount of hand selections when a task had to be executed, supports the account of Demanet et al. (in press) that the effect of stimulus repetitions in VTS is caused by stimulus-response associations that are formed when executing a task.

[1] This paper was co-authored by André Vandierendonck

INTRODUCTION

Top-down processes are involved when selecting the right actions in the appropriate situations and are often considered to be of main importance for goal-directed behavior (e.g. Miller & Cohen, 2001). The voluntary task switching (VTS) procedure was developed to investigate these processes involved in the selection and execution of tasks in a multi-tasking environment. In contrast with traditional task-switching procedures, where the sequence of tasks always is predefined by the experimenter, in the VTS procedure subjects are free to select the task to perform, as long as each task is selected an approximate equal number of times and tasks are selected in a random fashion (e.g. Arrington, 2008; Arrington & Logan, 2004, 2005; Liefooghe, Demanet, & Vandierendonck, in press, 2009; Mayr & Bell, 2006). This procedure was developed by Arrington and Logan (2004) based on the conviction that the switch cost in VTS can only reflect the duration of top-down processes, which are needed when switching tasks, because only a minimal amount of environmental support is provided and top-down control is indispensable for executing the selected task correctly. Recently, two recent studies confirmed that the switch cost in VTS is more stable and is less influenced by persisting task-set activation of preceding trials (Liefooghe et al., in press) and by variations in the experimental design (Liefooghe et al., 2009) than the switch costs observed in traditional task-switching procedures.

Because in VTS the task choice is free, the procedure does not only allow an investigation of the processes that are needed in task performance, but also the processes that are involved in task selection. Support for the distinction between processes of task selection and task performance was found in a study of Arrington and Yates (2009) in the observation that both are uncorrelated. In VTS, processes responsible for task selection can be investigated by studying the task-selection proportions as a function of variations in the design or the procedure (e.g. Arrington, 2008; Mayr & Bell, 2006; Arrington & Rhodes, in press; Weaver & Arrington, in press). A well-replicated finding with respect to task-selection proportions is that subjects tend to repeat tasks more often than expected by chance (e.g. Arrington & Logan, 2004) and that this tendency is stronger with shorter inter-trial intervals (ITIs; Arrington & Logan, 2005). This finding is known as the task-repetition bias. In view of the fact that in VTS subjects are instructed to generate tasks randomly this observation is quite surprising. Namely, in studies investigating random generation of simple events, in which similar instructions are given, typically an alternation bias is observed (Lopes, 1982; Lopes & Oden, 1987; Neuringer & Allen, 1986; Rapoport & Budescu, 1992; Treisman & Faulkner, 1987; Wagenaar, 1972). Arrington and Logan (2005) explained this discrepancy by arguing that the task-repetition bias in VTS results from a race between a heuristic based on random generation processes (representativeness heuristic) and a heuristic based on the availability of the tasks (availability heuristic). While the representativeness heuristic results in a tendency to alternate, as shown by Rapoport and Budescu (1997), the availability heuristic is assumed to result in a tendency to repeat tasks, because the previously executed task often is more available (or activated) than the other task due to persisting task-set activation. Arrington and Logan (2005) argued that the availability heuristic is dominant in short ITIs and can be overruled by the representativeness heuristic when ITI is long. Mayr and Bell (2006) proposed a similar account, namely that subjects have a natural tendency to repeat the tasks (see also Vandamme, Szmalec, Liefooghe, & Vandierendonck, in press) and that this tendency can be overruled by strategically driven inhibition processes.

In general, both accounts of the task-repetition bias can be translated into the hypothesis that switching between tasks is more difficult than repeating tasks and that, as a result, tasks are repeated more often, especially when the processes that are responsible to counteract this tendency are less efficient.

In a recent study (Demanet, Verbruggen, Liefooghe & Vandierendonck, in press), we found evidence for this hypothesis by observing that the number of task repetitions was boosted when tasks were selected voluntarily with a concurrent working memory (WM) load. This effect of load on the task-repetition bias is consistent with the hypothesis that top-down processes intervene to overrule the tendency to keep repeating the same task and that when these processes are less efficient due to a concurrent WM load, tasks are repeated more often. However, in a recent study, Liefooghe et al. (in press) observed that the repetition bias was stronger when the instruction to produce random task sequences was weakened at the start of the experiment. This finding could lead to the alternative hypothesis that the influence of a load on the repetition bias as observed in Demanet et al. (in press) is caused by the fact that processes involved in random generation were less efficient due to the WM load and not by a reduced efficiency of top-down control that is involved in a task choice.

In sum, in literature there is some but no conclusive evidence for the hypotheses that the size of the task-repetition bias and the impact of a WM load on this bias are related to the relative difference in difficulty when executing task repetitions and switches. However, this hypothesis was never tested directly. To settle this issue in the present study, we conducted two experiments where subjects still had to generate random sequences of events in conditions with and without a concurrent WM load, but where, in comparison with VTS, the difficulty of switching between events was drastically reduced.

Another important finding in the VTS literature is that, besides the general task-repetition bias, also external factors can bias a task choice. Mayr and Bell (2006) found that when a stimulus was immediately repeated, the chance to repeat the same task is higher than when the stimulus was alternated. In a recent study (Demanet et al., in press) we proposed an account for this stimulus-repetition effect. In a first experiment we found that this effect was stronger in conditions with than without a concurrent WM load. On the basis of two additional experiments, we concluded that the influence of stimulus repetitions is caused by the fact that on a subset of the trials no new task is selected but simply the same response is automatically triggered and executed when the stimulus is repeated. In other words, stimulus repetitions do not affect the task choice itself but make it more difficult to disengage from a previously executed action (see also, Hübner & Druey, 2006). We argued that a stimulus can prime a response through stimulus-response associations that are formed each time a subject is responding to a stimulus when performing a task (e.g. Logan, 1988). When this stimulus was repeated, the associated response is automatically activated. The observation that this effect was stronger with a concurrent WM load supports the conclusion that its size depends on the efficiency of top-down processes.

In the present study, we collected more direct evidence for the role of these associative response effects in VTS and the way they are overruled by top-down control processes. A first experiment investigated choice behavior when subjects were not required to select tasks randomly, but to select hands to perform a task, both in conditions with and without a concurrent WM load. In other words, subjects always had to execute the same task and on each trial, they could freely choose the hand to execute this task (see Figure 1, panel A). Because in this experiment a task still had to be executed and, as a consequence, a stimulus had to be translated into a correct response, we predicted that stimulus-response associations will be formed that affect the hand choice in a similar way as the task choice as observed in Demanet et al. (in press). In order to compare hand-selection and task-selection behavior, the selection proportions of this first experiment will be compared directly with Experiment 1 in Demanet et al. (in press). To this end, this first experiment was designed in such a way that the only difference between the present Experiment 1 and Experiment 1 of Demanet et al. (in press) was that no tasks but hands had to be selected randomly.

In a second experiment we also asked subjects to select hands randomly (see Figure 1, panel B), but in contrast with Experiment 1, subjects never had to execute a task on a stimulus. The presentation of the stimuli simply served as a probe for the next random response. In this experiment, the identity of the stimulus was irrelevant for the performance. Therefore we expect that no stimulus-response associations will be formed and stimulus repetitions will not affect the hand choice. By including this second experiment we also tested an alternative account for the stimulus-repetition effect. Namely, it is possible that this effect arises because subjects tune their selections to repeating or changing elements in the environment. According to this account stimulus repetitions would still have an effect when no tasks had to be executed. In order to compare these hand-selection proportions with the hand-selection proportions that we calculated in the present Experiment 1, Experiment 2 was identical to Experiment 1 except that no tasks had to be executed.

In addition, these two experiments allow us to investigate the selection proportions and the impact of a concurrent WM load on these proportions in situations where no tasks but hands had to be selected. On the basis of the hypothesis that the task-repetition bias is related to the difficulty to overrule task repetitions and on the basis of findings in studies investigating random generation (e.g. Rapoport & Budescu, 1997) we can predict to observe a tendency to alternate hands in both experiments. On the basis of the argumentation that the concurrent WM load hinders top-down processes that are responsible to counteract the tendency to repeat tasks (Demanet et al. in press), we can predict in both experiments that when no tasks had to be selected, the effects of load will disappear. This result would also confirm the findings of Baddeley, Emslie, Kolodny and Duncan (1998) who observed that when subjects had to generate random sequences of ten possible responses, the tendency to avoid immediate response repetitions was not affected by a concurrent WM load.

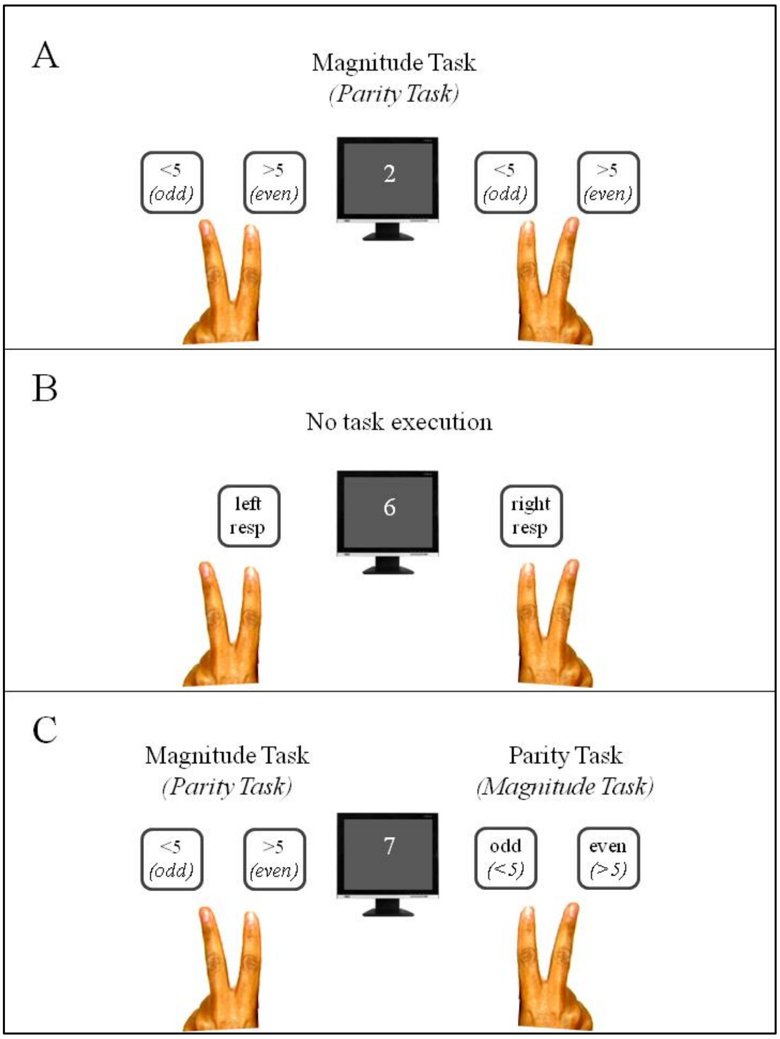

Figure 1: Panel A: Response mappings of Experiment 1: subjects had to perform one task while selecting hands randomly. Panel B: Response mappings for Experiment 2: subjects had to select left and right hands randomly, without executing a task. Panel C: Response mappings for Experiment 1 of Demanet et al. (in press): subjects had to execute the magnitude or the parity task randomly. Response mappings of the first mapping condition are presented in a normal font and response mappings of the second mapping condition are presented in *Italic.*

EXPERIMENTS

Because the method and result sections of the two experiments strongly overlapped, we described them together.

METHOD

Subjects, apparatus, tasks and stimuli. Forty-eight (Exp.1: 24; Exp.2: 24) students from Ghent University completed the experiments for course requirements and credit. They were tested individually by means of a Pentium III personal computer with a 17-inch color monitor running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). In the study phase a series of six consonants was presented. We avoided high phonological similarity within each list (Vandierendonck, De Vooght, & Van der Goten, 1998). The consonants were grouped into 13 low confusable groups based on their Dutch pronunciation: (B,D,P,T), (C), (F,S), (G), (H,K), (J), (L), (M, N), (Q), (R), (V, W), (X), (Z). Each list of 6 items was constructed by randomly selecting 6 pronunciation groups without replacement, and then randomly selecting one consonant within the group. For every subject, we selected 40 different lists. In the recall phase, subjects had to type the sequence of consonants on a keyboard in the order in which they were presented in the study phase. The keyboard was placed on the left of the subjects. Cues on the screen indicated which item (first, second…) in the sequence they had to generate. If they wanted they could restart entering the consonants by pressing the backspace key. In the test phase in Experiment 1, half of the subjects were asked to categorize a stimulus as smaller as or larger as ‘5’ (magnitude task) and the other half to categorize a stimulus as odd or even (parity task). This task could be performed with buttons assigned to the left or to the left hand (see Figure 1, panel A). The subjects were randomly assigned into two mapping conditions. The subjects of the first mapping condition performed the magnitude task and the subjects of the second mapping condition performed the parity task. Subjects performing the magnitude task had to press a left key (with the left or the right hand) for smaller than 5 and a right key (with the left or the right hand) for larger than 5. Subjects performing the parity task had to press a left key (with the left or right hand) for odd and a right key (with the left or right hand) for even numbers. In the test phase in Experiment 2 subjects were asked to press a button assigned to the left hand and a button assigned to the right hand (see Figure 1, panel B), in order to generate random sequences of hands without task execution. The identity of the stimulus was irrelevant in Experiment 2 and the stimulus onset served as a prompt for a next response. In both experiments we used digits 1-9, excluding 5 and the responses in the test phases were registered with an external response box that was placed in front of the subjects.

Procedure. Each series started with the study phase, in which six consonants were presented in the center of the screen at a rate of one consonant per second (500 ms on; 500 ms off). In the recall phase subjects were asked to recall the six consonants in the correct order, without any time constraints. At the end of the recall phase the percentage of correct recall was presented. In the test phase, each trial started with the presentation of a stimulus, which required a response within 3,000 ms. When a response was executed or when the maximal response time had elapsed, a fixed response-stimulus interval (RSI) of 100 ms started. Each test phase consisted of 13 stimuli. The first trial was considered a filler trial in order to exclude restart effects; of the remaining 12 trials, 3 trials were stimulus repetitions (25%) and 9 trials were stimulus alternations (75%). The percentage of stimulus repetitions deviated from the expected percentage of 12.5% stimulus repetitions when using eight stimuli. Each condition started with three practice blocks. In the first practice block, subjects practiced the study and recall phase separately. In the second practice block, subjects practiced the test phase separately. In a third practice block, subjects practiced the combination of the three phases. All training sessions were repeated until the subjects were confident in performing the three phases. Before the practice of the test phase (i.e. second practice block), in both experiments instructions based on the instructions of Arrington and Logan (2004) concerning unpredictability were displayed on the screen (in Dutch) and paraphrased if necessary. These instructions were adjusted for the random generation of hands. The practice blocks were followed by an experimental phase, which consisted of 20 lists per condition (load condition, study-test-recall or no-load condition, study-recall-test). The order of the conditions was counterbalanced over subjects. The experiment lasted approximately 40 minutes.

Results. The first trial of each VTS phase and trials following an error were discarded (data loss: Exp1 = 11.0%; Exp2 = 7.7%). In this study, we were particularly interested in the sequences of selected hands. Therefore, in the results section, we focused on the selection proportions only. Analyses of response latencies can be found in the Appendix. The selection proportions appear in Table 1 and the analyses in Table 2. The analyses on the selection proportions only were performed on the repetition proportions, because in the present study these are complementary with alternation proportions due to the binary sequences. We chose to report the analyses of the selection proportions in a step-wise order. First, we reported the results of the analyses on the hand-selection proportions obtained in Experiment 1. Second, we compared these hand-selection proportions with the task-selection proportions collected in Experiment 1 in Demanet et al. (in press) in order to investigate the differences between the selection of hands (with task execution) and the selection of tasks. Third, the analyses of the hand-selection proportions obtained in Experiment 2 were described. Finally, we compared these proportions with the hand-selection proportions in Experiment 1 in order to investigate the influence of a task execution on the sequences of hand selections.

Table 1: Selection proportions as a function of load, stimulus transition and hand\task transition for Experiment 1 and 2 and Experiment 1 of Demanet et al. (in press).

	no-load		***load***	
	hand repetitions	*hand switches*	*hand repetitions*	*hand switches*
Experiment 1				
stimulus repetitions	.56 (.04)	.44 (.04)	.56 (.04)	.44 (.04)
stimulus alternations	.41 (.02)	.59 (.02)	.44 (.02)	.56 (.02)
Experiment 2				
stimulus repetitions	.43 (.02)	.57 (.02)	.41 (.03)	.59 (.03)
stimulus alternations	.41 (.01)	.59 (.01)	.39 (.03)	.61 (.03)
	task repetitions	*task switches*	*task repetitions*	*task switches*
Exp. 1, Demanet et al. (in press)				
stimulus repetitions	.48 (.04)	.52 (.04)	.62 (.04)	.38 (.04)
stimulus alternations	.48 (.02)	.52 (.02)	.54 (.02)	.46 (.02)

Note – Standard errors are presented within brackets.

Hand-selection proportions of Experiment 1 (with task execution). First, an individual *t*-test was performed to test whether the proportions of hand repetitions differed from .50. This test showed that in general there was a trend to alternate between hands (M=.454, SE=.027; comparison .50: $t(23) = -1.69$, $p = .10$). Hand-repetition proportions were analyzed by means of a repeated measures ANOVA with load (no-load vs. load) and stimulus transition (stimulus repetition vs. alternations) as factors, with $\alpha = .05$. As can be seen in Table 2, the main effect of load was not significant indicating that hand-repetition proportions did not differ between the no-load (M=.485, SE=.027) and the load condition (M=.494, SE=.036). A main effect of stimulus transition was observed, indicating that on stimulus repetitions the proportion of hand-repetitions was higher (*M*=.560, *SE*=.042) than on stimulus switches (*M*=.418, *SE*=.027). This indicates that when generating hands to execute a task, the transition of a stimulus has a strong influence on the choice of hands. No interaction between load and stimulus transition was observed.

Hand-selection proportions of Experiment 1 vs. Task-selection proportions in Experiment 1 in Demanet et al. (in press). In order to investigate the similarities and differences between hand-selection and task-selection proportions, these proportions were subjected to a repeated measures ANOVA with load (no-load vs. load) and stimulus transition (stimulus repetition vs. alternation) as within-subjects factors and the generated event (hand vs. task) as a between-subjects factor. The results of this analysis (see Table 2) showed no main effect of event, indicating that tasks (*M*=.531, *SE*=.028) and hands (*M*=.489, *SE*=.028) were repeated equally often. The interaction between load and event was significant indicating that a WM load had a larger effect when tasks were selected. Stimulus transition and event also interacted, indicating that the stimulus-repetition effect was stronger when selecting hands than when selecting tasks. This significant interaction reveals the cause for the non-significant main effect of event. As shown in Table 1, tasks were repeated more often (*M*=.511, *SE*=.024) than hands (*M*=.418, *SE*=.023) when a stimulus was alternated, $F(1,46)=7.81$, $MSE=.0265$, $\eta_p^2= .15$. On stimulus repetitions, the selection proportions did not differ between hand (*M*=.560, *SE*=.040) and task selections (*M*=.550, *SE*=.040), $F<1$. Also, the three-way interaction between load, stimulus transition and event was significant indicating that in contrast with task selection, $F(1,23) = 12.96$, $MSE=.0034$, $\eta_p^2= .36$, the load and stimulus transition did not interact when hands are selected, $F(1,23) = 12.96$, $MSE=.0034$, $\eta_p^2= .36$.

Table 2: Outcome of the ANOVAs conducted on the selection proportions for Experiments 1 and 2 and of the ANOVAs used to compare hand-selection proportions obtained in Experiment 1 with the task-selection proportions obtained in Experiment 1 of Demanet et al. (in press), and with the hand-selection proportions obtained in Experiment 2.

		Experiment 1		
		Proportion hand repetitions		
	MSe	*(df1,df2)*	*F*	η_p^2
load	.0094	(1,23)	.21	.01
stimulus transition	.0293	(1,23)	16.35*	.42
load*stim trans	.0063	(1,23)	.09	.00
		Experiment 2		
		Proportion hand repetitions		
	MSe	*(df1,df2)*	*F*	η_p^2
load	.0082	(1,23)	1.14	.05
stimulus transition	.0082	(1,23)	1.93	.08
load*stim trans	.0119	(1,23)	.00	.00
		Hand selection (Exp. 1) vs. Task selection		
	MSe	*(df1,df2)*	*F*	η_p^2
event	.0763	(1,46)	1.09	.02
load	.0106	(1,46)	12.50*	.21
load*event	.0106	(1,46)	8.52*	.16
stimulus transition	.0274	(1,46)	14.19*	.24
stim trans*event	.0274	(1,46)	4.63*	.09
load*stim trans	.0049	(1,46)	3.66	.07
load*stim trans*event	.0049	(1,46)	5.70*	.11
		Hand (Exp. 2) vs. Hand (Exp. 1) selection		
	MSe	*(df1,df2)*	*F*	η_p^2
event	.0615	(1,46)	4.82*	.09
load	.0088	(1,46)	.15	.00
load*event	.0088	(1,46)	1.14	.02
stimulus transition	.0188	(1,46)	17.84*	.28
stim trans*event	.0188	(1,46)	8.54*	.16
load*stim trans	.0091	(1,46)	.04	.00
load*stim trans*event	.0091	(1,46)	.02	.00

Note – *: $p<.05$

Hand-selection proportions of Experiment 2 (without task execution). A *t*-test showed a tendency to alternate hands (*M*=.404, *SE*=.018; comparison .50: $t(23) = -5.24$, $p < .01$). Hand-repetition proportions were analyzed by means of a repeated measures ANOVA with load (no-load vs. load) and stimulus transition (stimulus repetition vs. alternations) as factors, with $\alpha = .05$. As can be seen in Table 2, the main effect of load was not significant indicating that the amount of hand repetitions did not differ between the no-load (*M*=.420, *SE*=.017) and the load condition (*M*=.401, *SE*=.024). Also, the main effect of stimulus transition was not significant, indicating that the proportion of hand-repetitions was similar on stimulus repetitions (*M*=.423, *SE*=.022) and on stimulus alternations (*M*=.398, *SE*=.019). The interaction between load and stimulus transition was not significant, $F<1$.

Hand-selection proportions in Experiment 2 vs. Experiment 1. In order to investigate the differences between hand-selection proportions when no task had to be executed (Experiment 2) and when a tasks had to be executed (Experiment 1), these proportions were subjected to a repeated measures ANOVA with load (no-load vs. load), stimulus transition (stimulus repetition vs. alternation) as within-subjects factors and the generated event (hand without task execution vs. hand with task execution) as a between-subjects factor. The results of this analysis (see Table 2) showed a main effect of event, indicating that hands were repeated more when a task had to be executed (*M*=.489, *SE*=.025) than without a task execution (*M*=.411, *SE*=.025). The interaction between load and event was not significant. Stimulus transition and event interacted, indicating that the stimulus-repetition effect on hand selection was more pronounced when a task had to be executed. This significant interaction reveals the cause for the main effect of event, because only on stimulus repetitions the hands were repeated more with (*M*=.560, *SE*=.034) than without a task execution (*M*=.423, *SE*=.033), $F(1,46)=8.19$, $MSE=.0544$, $\eta_p^{\,2} = .15$. On stimulus alternations no difference was observed between hand selections with (*M*=.418, *SE*=.023) and without a task execution (*M*=.398, *SE*=.023), $F<1$. The three-way interaction between load, stimulus transition and event was not significant.

Recall phase. The proportions of correct recall represent the probability that a particular item was remembered correctly in the correct order. We analyzed the proportions of Experiment 1 and 2 by means of a simple ANOVA with load as the only factor. As shown in Table 3, in both experiments, proportions of correct recall were higher in the no-load than in the load condition, which can be explained by the larger time interval in the load than in the no-load condition between the study and recall phases due to the different order of the phases.

Table 3: Mean proportions of correct recall in the no-load and load condition and the results of the main effect ANOVAs on these proportions with load as the only factor.

	no-load	load	main effect load			
			(df1,df2)	*F*	*MSe*	η_p^2
Experiment 1	.92 (0.1)	.82 (0.2)	(1,23)	44.28*	.0030	.66
Experiment 2	.97 (0.1)	.83 (0.3)	(1,23)	27.36*	.0101	.47

Note – *: $p<.05$. Standard errors are presented within brackets.

DISCUSSION

In the literature, the observed bias towards selecting more task repetitions than task switches in the VTS procedure (e.g. Arrington & Logan, 2004) does not seem to fit with the typically observed tendency to alternate between events in studies investigating random generation (e.g. Rapoport & Budescu, 1997).

A first goal of the present study was to test the hypothesis that the repetition bias is related to the fact that switching between tasks is more difficult than repeating tasks and that as a result tasks are repeated more often (Arrington & Logan, 2005; Mayr & Bell, 2006). We observed in two experiments that when no tasks but hands had to be selected, the proportion of repetitions was lower than one could expect on the basis of chance (.50). This hand-alternation bias confirms previous findings in the random generation literature (e.g. Baddeley et al., 1998; Rapoport & Budescu, 1997) and supports the hypothesis that the task-repetition bias typically observed in VTS is related to the requirement to select tasks rather than hands (see Arrington & Logan, 2005; Mayr & Bell, 2006). In our view, a task selection is different from the selection of hands, because the selection of a task repetition or a task switch has large consequences in the subsequent task execution. In Demanet et al. (in press) was found that it is much easier to repeat than to switch tasks, while the difference in performance between hand repetitions and hand switches is much smaller (see Appendix). The idea that the consequences of a choice can drive this choice can be related to the 'law of least mental effort' introduced by Balle (2002) which states that people develop a tendency to avoid situations that need high levels of metal effort when given the choice. This interpretation is also supported by recent findings of Botvinick and Rosen (in press) who observed that subjects learn to avoid situations with a large amount of task switches.

In sum, the present study showed that when a selection of a switch of an event does not have large repercussions for the amount of effort that needs to be invested, the tendency to avoid switches of that event disappears completely.

A second goal in the present study was to test the account proposed in Demanet et al. (in press) that the higher task-repetition bias with than without a concurrent WM load is related to a reduced efficiency of top-down control to overcome the task-repetition tendency. This hypothesis was supported by the observation that the effects of WM load disappeared completely when hands were selected. With this finding we also confirmed the findings of a study of Baddeley and colleagues (1998) where was observed that a WM load does not affect the number of repetitions in a sequence of randomly generated numbers. Most importantly, it also rejects the hypothesis that the effect of the concurrent WM load observed in Demanet et al. (in press) is caused by the fact that random-generation processes were less efficient.

In our view, the present findings together with the findings of Liefooghe, et al. (in press), in which is observed that tasks are repeated more when the random instruction is weakened, can be considered as evidence for the idea that a voluntary task selection results from an interplay between random generation processes and other processes that are particularly involved when tasks are selected. In a recent study (Vandierendonck, Demanet, Liefooghe, & Verbruggen, submitted) we proposed a model in which both kinds of processes are incorporated and in which is assumed that a voluntary task selection is based on the automatic retrieval of chains of task-related information that are stored in long-term memory.

A third goal in the present study was to unravel the mechanisms behind the stimulus-repetition effect (Mayr & Bell, 2006). In Demanet et al. (in press) we argued that this effect is caused by the fact that each stimulus that has to be translated into a correct response becomes automatically associated with that response (see also, Logan, 1988). The observation in Experiment 1 that hands are repeated more often on stimulus repetitions than on stimulus alternations supports this account. Hence, when a hand is selected to execute a task, the stimulus still has to be translated into the correct response, resulting in an association between that stimulus and that response. Also the finding in Experiment 2 that the stimulus-repetition effect disappeared when stimuli were not translated into a response is in line with this account.

Finally, in contrast with Experiment 1 in Demanet et al. (in press), where only a stimulus-repetition effect was found under a concurrent WM load, in the present Experiment 1, the stimulus-repetition effect was equally strong in conditions with and without a WM load. This observation seems to suggest that an exclusive function of task selection, in contrast with hand selection, is to shield behavior from automatically triggered responses, and that this function depends on the efficiency of top-down control. Possibly, this account can be related to the concept of goal-shielding of Goschke and Dreisbach (2008).

To conclude, in the present study we found strong evidence in support of the hypotheses that the task-repetition bias in VTS and the effect of a concurrent WM load on this bias is related to the relative difference in difficulty between repeating and switching tasks. We also found strong evidence for the idea that the stimulus-repetition effect (e.g. Mayr & Bell, 2006) is caused by associations between a stimulus and a response that are formed during task execution. In addition, we found support for the idea that top-down processes in voluntary task selection, in contrast with random hand selection, are necessary to shield task selection from external factors (see also Goschke & Dreisbach, 2008). In sum, this study clearly shows that voluntary task selection is more than just random generation of hands and, as a consequence, can be considered as a useful tool to investigate intentional goal-directed behavior.

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APPENDIX

The mean RTs and analyses are presented in Tables A1 and A2. Error rates were very low (Exp1 = 3.2%; Exp2 = 0.0%) and were therefore not analyzed further.

We analyzed the mean RTs of Experiments 1 and 2 with a repeated measures ANOVA with the factors load (no-load vs. load), stimulus transition and hand transition (repetition vs. switch). In Experiment 1 a main effect of hand transition was observed indicating that responses were faster on hand repetitions (*M*=622ms, *SE*=19) than on hand switches (*M*=690, *SE*=20). The main effect of stimulus transition was also significant, indicating that repetitions of stimuli (*M*=618ms, *SE*=25) induced faster responses than alternations (*M*=694ms, *SE*=16). In Experiment 1, the interaction between stimulus transition and hand transition was reliable indicating that stimulus repetitions speeded up the responses more when hands were repeated than when hands were switched. No other effects or interactions were reliable in Experiment 1. For Experiment 2, none of the effects or interactions was significant; indicating that neither load, nor stimulus transition nor hand transition influenced the response latencies.

Table 1A: Mean RTs as a function of load, stimulus transition and hand transition for Experiment 1 and 2.

	no-load		***load***	
Experiment 1	*hand repetitions*	*hand switches*	*hand repetitions*	*hand switches*
stimulus repetitions	535 (24)	678 (29)	583 (37)	677 (34)
stimulus alternations	671 (18)	694 (21)	700 (16)	712 (21)
Experiment 2				
stimulus repetitions	369 (36)	372 (41)	321 (37)	330 (38)
stimulus alternations	372 (38)	355 (30)	323 (38)	337 (35)

Note – Standard errors are presented within brackets.

Table 2A: Outcome of the ANOVAs conducted on the RTs for Experiments 1 and 2.

	Experiment 1			
	MSe	*(df1,df2)*	*F*	η_p^2
load	18434	(1,23)	1.44	.06
stimulus transition	24856	(1,23)	11.16*	.33
hand transition	15496	(1,23)	14.21*	.38
load*stim trans	4168	(1,23)	.00	.00
load*hand trans	2688	(1,23)	4.11	.15
stim trans*hand trans	4718	(1,23)	25.54*	.53
load*stim trans*hand trans	1775	(1,23)	2.34	.09

	Experiment 2			
	MSe	*(df1,df2)*	*F*	η_p^2
load	18739	(1,23)	3.85	.14
stimulus transition	870	(1,23)	.11	.00
response transition	7109	(1,23)	.04	.00
load*stim trans	379	(1,23)	4.10	.15
load*hand trans	1516	(1,23)	2.64	.10
stim trans*hand trans	2341	(1,23)	.31	.01
load* stim trans*hand trans	2566	(1,23)	.77	.03

Note – *: p<.05

CHAPTER 4
RESPONSE-SEQUENCES EFFECTS IN THE VOLUNTARY SELECTION OF TASKS

Manuscript under revision[1]

Previous research has shown that the selection of tasks in the voluntary task switching procedure is based on an interaction between top-down processes and bottom-up influences (Arrington, 2008; Demanet, Verbruggen, Liefooghe, & Vandierendonck, in press). In two experiments, in which a double-registration procedure was used, we observed that task selections were guided by sequences of preceding actions. This finding indicates that even with a double-registration procedure a voluntary task selection is never truly voluntary and is always biased by bottom-up factors. Over the two experiments, we also found evidence for the idea that the efficiency of top-down processes that are responsible to counteract influences of bottom-up depends on strategic modulations.

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[1] This paper was co-authored by Baptist Liefooghe, André Vandierendonck and Frederick Verbruggen

INTRODUCTION

A key facet of executive control relates to how people can change their behavior in order to achieve different task goals. The task-switching paradigm allows investigation of the ability to shift between different tasks. Traditionally, in this paradigm subjects perform a series of tasks that are imposed by the experimenter (for reviews, see Logan, 2003; Monsell, 2003). The longstanding idea is that the switch cost (i.e., the impaired performance on task switches compared to task repetitions) observed in this paradigm provides a valid measure of the executive processes that are necessary to configure the cognitive system when switching between tasks. However, in several studies was found that factors unrelated to a task switch, such as stimulus-response associations (e.g. Allport & Wylie, 2000), cue-related processes (e.g. Logan & Bundesen, 2003), stimulus-task associations (e.g. Waszak, Hommel & Allport, 2003) and preceding task sequences (Schneider & Logan, 2005) can affect the switch cost, suggesting that this cost does not represent the duration of switch-related processes. A second problem with traditional task-switching procedures is that they only allow us to investigate a subset of the processes that are used when switching tasks in daily life, because in most situations we are not told to switch from one task to another on command but we can choose the tasks we want to perform. Therefore, in our view, these procedures are lacking ecological validity.

In order to overcome these problems with the traditional task-switching procedures, Arrington and Logan (2004; 2005) introduced the voluntary task switching (VTS) procedure (see also; Arrington, 2008; Forstmann, Brass, Koch, & von Cramon, 2006; Forstmann, Ridderinkhof, Kaiser, & Bledowski, 2007; Liefooghe, Demanet, & Vandierendonck, 2009; Lien & Ruthruff, 2008; Mayr & Bell, 2006). In this procedure subjects are free to select the task to perform, as long as each task is selected an approximate equal number of times and subjects do not follow a predictable pattern of task selections. Typically, in VTS a single-registration procedure is used in which one task is mapped to the left hand and the other task to the right hand (e.g. Arrington & Logan, 2004; 2005; Demanet, Verbruggen, Liefooghe, & Vandierendonck, in press; Mayr & Bell, 2006).

With respect to the problem of the switch cost, recent studies have shown that the switch cost in VTS is less contaminated by other factors such as proactive task interference (Liefooghe, Demanet, & Vandierendonck, in press) and by variations in the experimental design (Liefooghe et al., 2009). These studies suggest that the switch cost in VTS can be considered as an accurate measure for executive processes involved when switching tasks.

With respect to the problem of ecological validity, the VTS procedure was designed to investigate the processes involved in voluntary task selection and the factors that bias a voluntary task choice. In VTS, a frequently replicated finding is that subjects tend to repeat the tasks more often than expected by chance, especially with short inter-trial intervals (ITIs). Several accounts for this so-called task-repetition bias have been proposed. Arrington and Logan (2005) argued that it is caused by a competition between task selection and task execution processes. When the ITI is short, the subjects are confronted with a dual-task situation in which they have to select a task and configure the cognitive system to execute this task in a minimum of time. Selecting a task repetition reduces this overlap because preparing for a task repetition is less time-consuming than preparing for a task switch (e.g. Rogers & Monsell, 1995). When ITI is long, this overlap is already minimal regardless of whether a task repetition or a task switch is selected, leading to a reduction of the repetition bias. Mayr and Bell (2006) suggested that subjects have a natural tendency to stick with the most active task set and that this tendency can be overruled by strategically driven inhibition processes. The more they inhibit the no-longer relevant preceding tasks in the ITI, the lower the task-repetition bias will be. Mayr and Bell also argued that the strength of this inhibition depends on the strategy to treat consecutive task selections as discrete events. In our view, both these accounts of the repetition bias can be related to the ‘law of least mental effort’ introduced by Balle (2002), which entails that people will always develop a tendency to avoid situations that need high levels of cognitive control. Consistent with that idea, Botvinick (Botvinick, 2007; Botvinick & Rosen, in press) demonstrated that subjects learn to avoid situations involving many task switches when given the chance.

In addition, Mayr and Bell (2006) observed that elements in the environment can boost the task-repetition bias. They found that tasks were repeated more when a stimulus was repeated, especially when stimulus repetitions were frequent. In a recent study (Demanet et al., in press) evidence was reported that suggests that this stimulus-repetition effect is caused by previously formed stimulus-response associations and that on a proportion of trials, especially on stimulus repetitions, a response is executed without an actual task selection. The observation that on a part of the trials no task is selected seems to question the idea that VTS with a single registration is an appropriate procedure to investigate voluntary task selection.

A potential solution for this problem was already introduced by Arrington and Logan (2005; Experiment 6). They used a double-registration variant of VTS, in which each trial consists of two parts. First, a probe (‘?’) is presented, instructing the subjects to indicate which task they choose to perform. Second, a stimulus is presented, to which the selected task must be applied (see Figure 1 for an example of a particular trial). In other words, by requiring an additional task-selection response, subjects were forced to make a task choice before they executed the task. Because the task-selection response is assumed to reflect task-selection processes, and the second response (i.e., the task-execution response) is assumed to reflect task-execution processes, one could argue that this procedure can be used to examine the task-selection processes uncontaminated by task-execution processes. By replicating the task-repetition bias with double registration, the results of Arrington and Logan (2005, Experiment 6) suggested that the general repetition bias in VTS, at least with this procedure, is caused by choice-related processes, and not only by simple re-executions of the same task as observed by Demanet et al. (in press). Because the probe was the same on all trials and because the target did not appear until the task choice was made, there were also no external stimuli that could have affected the task choice. Both these considerations could lead to the hypothesis that when one wants to investigate voluntary task choice independent of external factors, the double-registration variant of VTS is an appropriate tool.

The main goal of the present study was to investigate if this hypothesis holds or that, on the contrary, by introducing an extra task-selection response, new sequence effects on the task choice are created. Based on recent research (Demanet et al., in press, Experiment 2) where was shown that even the repetition of task-irrelevant features can strongly bias the task selections (more task repetitions on feature repetitions), we could predict that preceding actions that are generated by the subject him or herself will have a similar effect on the task selections. In the present study we will test this issue directly by investigating whether a task choice can be affected by repeating responses on preceding trials in VTS with double registration. The effect of these response sequences was investigated by manipulating the relation of the task-execution responses of trial *n-2* and trial *n-1* (see Figure 1) and by testing whether the task selection on trial *n* is influenced by this relation (response repetition vs. alternation). If response sequences indeed have an effect on following task selections, we expect to find more task repetitions following task-execution response repetitions than following task-execution response alternations. In order to investigate if the occurrence of this potential sequential effect depends on particular conditions and to investigate its underlying mechanism, two additional factors were manipulated.

A first factor we manipulated was the time between the stimulus presentation on trial *n-1* and the presentation of the probe on trial *n* (stimulus-probe interval; SPI). The rationale behind this manipulation is that the efficiency of top-down control, which is involved when selecting tasks voluntarily, depends on the length of the SPI (for a similar manipulation see Arrington, 2008). Arrington observed that external influences on task choice in VTS were stronger when little time is available to select a task. According to this finding, we predicted that also sequential effects will be stronger when the SPI was short. To investigate this in Experiment 1, SPI was manipulated as a within-subjects factor with four levels (50; 300; 1,000; and 1,500ms).

Second, we manipulated the alignment of the task-selection and the task-execution responses in two alignment conditions (horizontal vs. orthogonal alignment). According to a study of Elsner and Hommel (2004) one could predict that the task-execution response of trial *n-2* and the task-selection response on trial *n-1* can become temporarily associated when the execution response and selection response occur in close succession, especially when SPI is short (see Figure 1). When the task-execution response is immediately repeated on trial *n-1*, the associated task-selection response could be automatically activated, leading to more task repetitions following task-execution repetitions. We argue that when the potential sequential effects are caused by these associations, one should find that these are stronger when the spatial codes of the selection and execution responses overlapped strongly (as in the horizontal alignment condition) than when the spatial codes did not overlap (as in the orthogonal alignment condition; see Figure 2; see also Lien & Proctor, 2000).

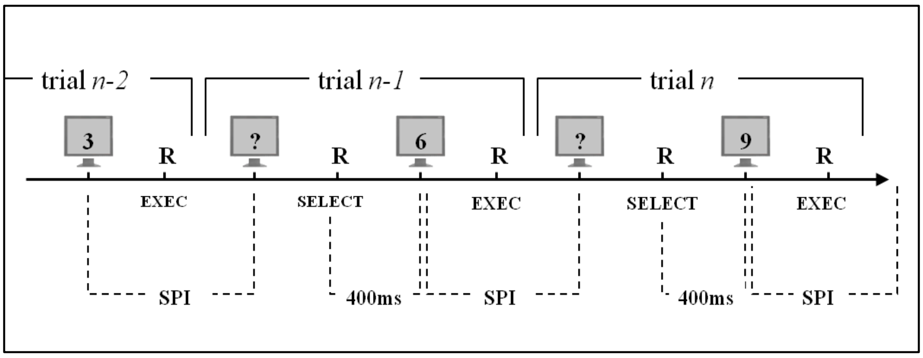

Figure 1: An example of three consecutive trials in the double-registration procedure of voluntary task switching. SELECT = task-selection response; EXEC = task-execution response.

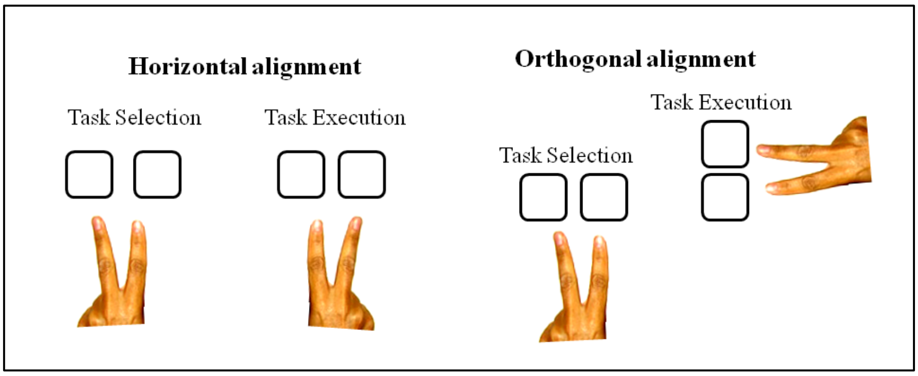

Figure 2: Horizontal and orthogonal alignment conditions. The Delete and End keys from a normal keyboard were always assigned to the left hand. For the right hand, 7 and 8 (horizontal alignment) or PageDown and PageUp (orthogonal alignment) were used.

EXPERIMENT 1

METHOD

Subjects. Forty first-year psychology students (twenty subjects per condition) at Ghent University participated for course requirements and credit. All subjects had normal or corrected-to-normal vision, were right-handed, and all were naïve to the purpose of the experiment. Subjects were randomly assigned to one of the alignment conditions.

Materials. Stimuli were the digits 1–9, excluding 5. Subjects were required to judge either the magnitude of the digit (smaller or larger than five) or its parity (odd or even). Responses were registered by means of the numeric pad of a standard keyboard. Two sets of response keys were defined, and each set was assigned to a different hand. One hand was used for pressing the task-selection keys; the other hand was used for pressing the task-execution keys. The specific assignment of the task-selection and task-execution keys depended on the alignment condition (see Figure 2).

Procedure and design. Subjects were tested by means of Pentium III personal computers with a 17-inch color monitor. All experimental procedures reported in this paper were administered using the Tscope C/C++ library (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Each session lasted for approximately 45 minutes. After subjects signed an informed consent, instructions were presented on screen and paraphrased if necessary. The instructions concerning unpredictability of voluntary task switches were the same as those used by Arrington and Logan (2005).

On each trial, a probe (‘?’) was presented 5 mm above the centre of the screen. When subjects pressed a task-selection key, the probe disappeared and was followed 400 ms later by the stimulus, which appeared 5mm below the centre of the screen. Stimuli were selected in such a way that the task-execution responses were repeated on 50% of the trials. The stimulus remained on screen until subjects responded to the selected task or until a maximal response time of 2,500 ms elapsed. The probe of trial n appeared 50; 300; 1,000 or 1,500 ms after the presentation of the stimulus of trial *n-1*. SPI varied on a trial-to-trial basis. Subjects were assigned randomly to two alignment conditions, which differed in the overlap in response codes between task-selection and task-execution responses.

Subjects first performed two practice blocks of 64 trials, followed by four experimental blocks of 256 trials. In the first practice block, the familiarization of the procedure of selecting and executing the different tasks was emphasized. In the second practice block, the random generation of the tasks was emphasized. In order to make the subjects more aware of their selection behavior, the warning ‘do not forget to switch tasks’ appeared for 1,000ms whenever the subjects repeated a task four times in a row; when the subjects switched between tasks four times in a row the warning ‘do not forget to repeat tasks’ appeared for 1,000ms. The task-selection feedback was presented in the second practice block only.

During the entire experiment, subjects received on-line feedback about their performance. A red screen appeared for 50ms when they made an error on the target. When they were too slow to select a task (> 2,500ms), the sentence ‘no task selected’ was presented. Following each block (practice and experimental) a general summary about the performance during that block was presented. This feedback consisted of the mean reaction times on the targets, the percentage of errors, the selection percentage of each task, the percentage of failures to select a task, and the percentage of task repetitions and task switches. If necessary, subjects were corrected. They were urged to switch more or repeat more, when the proportion of repetitions or switches was above .70, respectively. They were urged to make fewer errors when percentage of errors was above 15%, and to respond faster when mean task-execution reaction time was above 1,200 ms or when the proportion of trials without a task-indication response was above 10%. Finally, they were urged to be more random when they selected a particular task on more than 75% of the trials.

RESULTS

For the analyses of task-selection proportions, only trials on which a task was selected and trials following trials with a correct task-execution response were used. Also trials following exact stimulus repetitions were excluded in order to avoid aftereffects of stimulus repetitions. This resulted in the loss of 21.1% of the trials. All analyses in this study are based on MANOVAs, the reported *F*-values are approximations to Wilks' lambda. Several task-switching studies have demonstrated that response-sequence effects on task execution can be influenced by the transition of the task. For example, on task-repetition trials, a response-repetition benefit is observed, whereas on task-switch trials, this benefit is typically no longer observed and even a response-repetition cost is found (e.g. Kleinsorge, 1999; Schuch & Koch, 2004). For that reason, in the present study we included task transition of trial *n-1* in the analyses of the task-repetition proportions. The analyses concerning the task-execution latencies and error rates do not belong to the main concern of this study; for completeness, they are presented in Appendix A.

The proportion of task repetitions was subjected to a 2 (alignment: horizontal vs. orthogonal) by 4 (SPI: 50; 300; 1,000 vs. 1,500ms) by 2 (task transition on trial *n-1*: task repetition vs. task switch) by 2 (response transition on trial *n-1*: response repetition vs. response alternation) mixed MANOVA with repeated measures on the last three factors. Mean proportions are presented in Figure 3. We found that the task-repetition bias on trial *n* was influenced by execution-response repetitions on trial *n-1*: the proportion of task repetitions on trial *n* was higher when trial *n-1* was an execution-response repetition (*M*=.646, *SE*=.02) than when trial *n-1* was an execution-response alternation (*M*=.615, *SE*=.02), $F(1,38)=15.85$, $p<.01$, $\eta_p^2= .29$. The task-repetition proportions were also influenced by task transition on trial *n-1*: the proportion of task repetitions on trial *n* was lower when trial *n-1* was a task repetition (*M*=.486; *SE*=.02) than when it was a task switch (*M*=.775; *SE*=.02), $F(1,38)=256.87$, $p<.01$, $\eta_p^2= .87$. The interaction between response transition and task transition on trial *n-1* was significant, $F(1,38)=6.09$, $p=.02$, $\eta_p^2= .14$, indicating that the effect of a response transition was stronger when trial *n-1* was a task repetition than when it was a task switch (Figure 3). Planned comparisons showed that the response-sequence effect was significant following task repetitions, $F(1,38)=12.44$, $p<.01$, $\eta_p^2= .25$, and marginally significant following task switches, $F(1,38)=3.96$, $p=.05$, $\eta_p^2= .09$. This interaction between response transition and task transition can possibly be linked to the interaction between task transition and response transition that we found on the task-execution latencies (Appendix A): consistent with previous research (see e.g. Schuch and Koch, 2004), a response-repetition advantage was observed when repeating tasks, which transformed into a response-alternation advantage when switching tasks (see Table A1). The main effect of SPI was also reliable, $F(3,36)=14.22$, $p<.01$, $\eta_p^2= .54$, indicating that task-repetition proportions were larger the shorter the SPI (SPI-50ms: *M*=.660, *SE*=.02; SPI-300ms: *M*=.645, *SE*=.02; SPI-1,000ms: *M*=.625, *SE*=.02; SPI-1,500ms: *M*=.592, *SE*=.02). No other effects or interactions were significant.

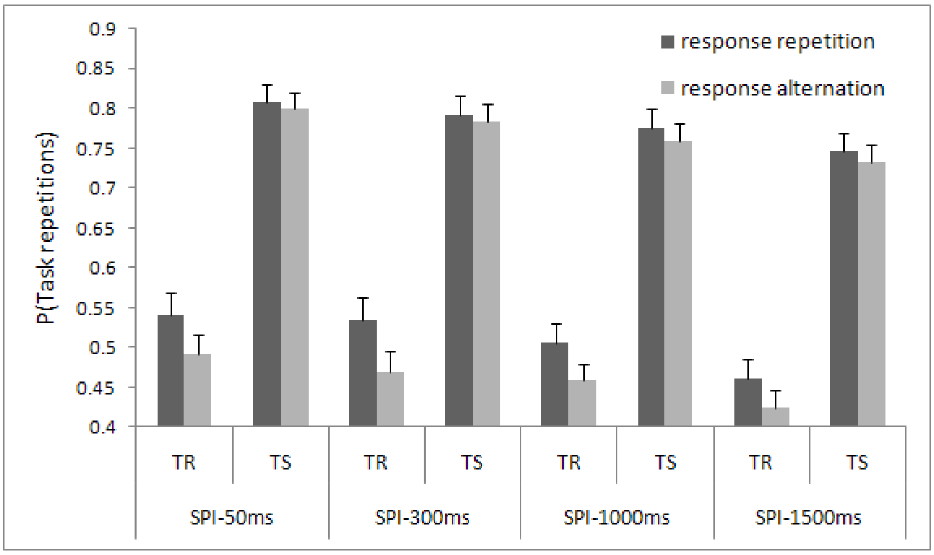

Figure 3: Proportion of task repetitions as a function of SPI, task transition on trial *n-1,* and task-execution response transition on trial *n-1,* for Experiment 1. TR=task repetition on trial *n-1*; TS=task switch on trial *n-1*. *Vertical bars denote standard errors.*

With respect to task-selection RTs, we were only interested in the main effect of SPI[2]. This main effect was significant, $F(3,37)=542.95$, $p<.01$, $\eta_p^2= .98$, indicating that RTs were faster the longer the SPI (SPI-50ms: *M*=1146, *SE*=26; SPI-300ms: *M*=895, *SE*=28; SPI-1,000ms: *M*=388, *SE*=12; SPI-1,500ms: *M*=378, *SE*=15).

[2] In the main text we did not report these latency data in the same way as for the task-repetition proportions because we would need a five-way MANOVA (i.e., ‘response properties trial *n-1’* x ‘task-switch properties trial *n-1*’ x ‘task-switch properties trial *n*’ x SPI x mapping condition). The theoretical relevance of this analysis for the interpretations of the selection proportions—which are our main focus—is low. The main effect of SPI obtained with this MANOVA was significant and did not differ from the main effect reported in the main text.

DISCUSSION

The results of Experiment 1 were straightforward. Subjects repeated tasks more than they switched and this bias decreased with longer SPIs. Of central importance for the present study is that the proportion of task repetitions on trial *n* was higher when the task-execution response of trial *n-2* was repeated, than when the task-execution response alternated on trial *n-1*. In other words, repetition of task-execution responses on trial *n-1* resulted in a higher amount of task repetitions on trial *n*. Another important finding is that this effect was strong following a task repetition and was seriously reduced following a task-switch trial. The strength of the sequence effect did not depend on the alignment condition. The theoretical implications of these findings will be discussed in the General Discussion.

Opposed to the expectations, the response-sequence effects were not affected by SPI. This observation seems to suggest that response sequences can bias task selection independently of the efficiency of top-down control. However, according to Poulton's (1982) asymmetric-transfer hypothesis it is possible that when factors (e.g. SPI) are manipulated in within-subject designs a strategy that is adopted in one condition transfers to the other conditions where this strategy would normally not be adopted. A possible way to investigate this is to vary SPI as a between-subjects variable, and this is exactly what we did in Experiment 2. Two SPIs were used, namely the two extreme values used in Experiment 1 (50ms vs. 1,500ms). A comparison of the course of the response-sequence effects in Experiment 1 and 2 over different SPIs can help us to understand the nature of the sequence effects. A replication of the response-sequence effects that are independent of SPI in Experiment 2 would support the idea that response sequences indeed have a structural effect on task selection independent of the time available for this selection and of the strength of top-down control. If a different course of the response-sequence effect over SPIs is observed in Experiment 2, this would support the idea that this effect depends on the involvement of strategies.

EXPERIMENT 2

METHOD

Subjects. Eighty first-year psychology students at Ghent University participated for course requirements and credit. They were randomly assigned to the four cells that resulted from the factorial design of the two SPI and two alignment conditions. This resulted in twenty subjects per cell. Subjects had normal or corrected-to-normal vision, were right-handed, all were naïve to the purpose of the experiment, and none of them had participated in Experiment 1.

Materials and procedure. These were the same as in Experiment 1 except for the following: we used the two extreme values of SPI from Experiment 1 (50ms vs. 1,500ms). There were two experimental blocks of 256 trials.

RESULTS

The same exclusion criteria as in Experiment 1 were applied. This resulted in the loss of 22.6% of the trials. The analyses concerning the task-execution latencies and error rates are presented in Appendix B.

Task-repetition proportions were subjected to a 2 (alignment: horizontal vs. orthogonal) by 2 (SPI: 50ms vs. 1,500ms) by 2 (task transition on trial *n-1*: repetition vs. switch) by 2 (response transition on trial *n-1*: repetition vs. alternation) mixed MANOVA with repeated measures on the last two factors. Mean proportions are presented in Figure 4.

Consistent with Experiment 1, we found that the proportion of task repetitions was higher when trial *n-1* was an execution-response repetition (M=.649, SE=.02) than when it was an execution-response alternation (M=.610, SE=.02), $F(1,76)=39.65$, $p<.01$, $\eta_p^2 = .35$. Also, the proportion of task repetitions was higher after a task switch (M = .746; SE=.02) than after a task repetition (*M* = .513; *SE*=.02), represented by a main effect of task transition, $F(1,76)=132.82$, $p<.01$, $\eta_p^2= .63$. The interaction between task transition and response transition was significant, $F(1,76)=34.02$, $p<.01$, $\eta_p^2= .36$. The effect of response repetitions on task proportions was observed following a task repetition, $F(1,76)=67.48$, $p<.01$, $\eta_p^2= .48$, but not following a task switch, $F<1$.

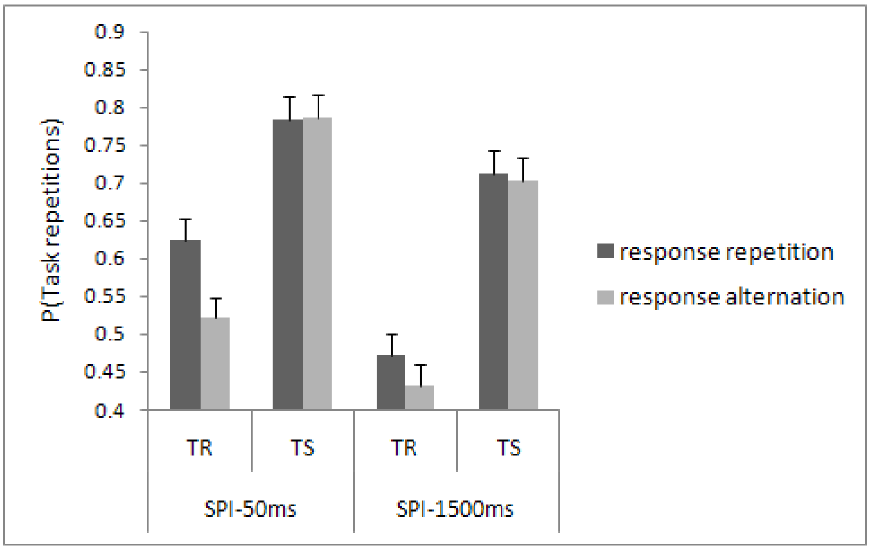

Figure 4: Proportion of task repetitions as a function of SPI, task transition on trial *n-1,* and task-execution response transition on trial *n-1* for Experiment 2. TR=task repetition on trial *n-1*; TS=task switch on trial *n-1*. *Vertical bars denote standard errors.*

The main effects of alignment, $F(1,76)=5.80$, $p<.05$, $\eta_p^2= .07$, and SPI, $F(1,76)=8.19$, $p<.01$, $\eta_p^2= .10$, were significant. The task-repetition bias was higher in the orthogonal alignment (*M*=.671, *SE*=.02) than in the horizontal alignment condition (*M*=.588, *SE*=.02). Also, the task-repetition bias was higher in the SPI-50ms (*M*=.679, *SE*=.02) than in the SPI-1,500ms condition (*M*=.580, *SE*=.02). The factor response transition interacted with SPI, $F(1,76)=4.46$, $p<.05$, $\eta_p^2= .06$, suggesting that the sequence effect was more pronounced when SPI was short. Planned comparisons showed that the effect of response transition was significant in the SPI-50 ms, $F(1,76)=35.35$, $p<.01$, $\eta_p^2= .32$, and in the SPI-1,500ms condition, $F(1,76)=8.76$, $p<.01$, $\eta_p^2= .10$. Finally, the three-way interaction between task transition, response transition and SPI was reliable, $F(1,76)=10.10$, $p<.01$, $\eta_p^2= .12$. Figure 4 shows that the interaction between task transition and response transition is more pronounced in the SPI-50ms than in the SPI-1,500ms condition. No other interactions were significant with the highest *F*-value for the interaction between SPI and alignment condition, $F(1,76)=1.80$, $p=.18$, $\eta_p^2=$ .02.

In the task-selection RTs the main effect of SPI again was significant[3], $F(1,78)=578.23$, $p<.01$, $\eta_p^2= .88$, indicating that RTs were much faster in the SPI-1,500ms (*M*=318, *SE*=18) than in the SPI-50ms condition (*M*=946, *SE*=18).

DISCUSSION

The results of Experiment 2 are for the most part in line with the results of Experiment 1. A task-repetition bias was observed that was stronger when SPI was short. The response-sequence effect was replicated and we again observed that this effect was stronger following task repetitions than following task alternations. Also, we replicated the finding that the strength of the response-sequence effect did not depend on the alignment condition. However, in contrast with Experiment 1 the alignment of the

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[3] As in Experiment 1, the main effect of SPI observed with a five-way MANOVA (i.e., ‘response properties trial *n-1’* x ‘task-switch properties trial *n-1’* x ‘task-switch properties trial n’ x SPI x mapping condition) was identical to the effect of SPI that is reported in the main text.

responses affected the general tendency to repeat tasks. We have yet no explanation for this inconsistency.

Interestingly, in contrast with Experiment 1, the size of the response-sequence effects in Experiment 2 depended on the length of the SPI. Namely, these effects were stronger in the short than in the long SPI condition. In line with Poulton's (1982) argumentation, the observation that the course of the sequence effect over SPIs depends on how SPI is manipulated (within- vs. between-subjects) supports the idea that the size of this effect depends on the use of strategies. These findings will be discussed in the General Discussion.

GENERAL DISCUSSION

In the present study, we investigated whether voluntary task selections were influenced by sequences of preceding actions. To obtain a direct measurement of task-selection processes uncontaminated by task-execution processes of the selected task we used a double-registration procedure for VTS. This procedure was introduced by Arrington and Logan (2005; experiment 6) to provide a clean measure of the processes involved when selecting tasks voluntarily. The main goal of the present study was to investigate that by introducing an additional response in double registration, new sequential effects are induced.

In both experiments we found that sequences of preceding actions can affect a task choice, even when a double-registration methodology is used and in conditions in which sufficient time is provided to select a task voluntarily. We observed that tasks were repeated more when preceded by a task-execution response repetition than when preceded by a response alternation. We also observed that this response-sequence effect was reduced strongly (Experiment 1) and even eliminated (Experiment 2) when both responses were given in the context of a different task.

In our view, this finding can help us to understand the mechanisms behind these sequence effects because it suggests that a task repetition was not primed by the response itself but by the stimulus category with which this response was associated. In the task-switching literature, a stimulus category often is interpreted as the meaning of the response when performing a particular task (e.g. Meiran, Chorev & Sapir, 2000, Schuch & Koch, 2004). In the present study, left responses were associated with the stimulus categories, 'smaller than five', or 'odd', while right responses were associated with the stimulus categories, 'larger than five', or 'even'. Only when both consecutive responses were executed in the context of the same task, they were also associated with the same stimulus category. More evidence for the formation of such associations can be found in the task-execution latencies (Appendices A and B). We found that response repetitions were faster than response alternations when the task was repeated, while response alternations were faster than response repetitions when the task was switched (e.g. Schuch & Koch, 2004). In our view, the finding that response repetitions only primed a task repetition when both responses represented the same stimulus category seems to suggest that not response repetitions but stimulus-category repetitions primed the selection of a task repetition. Possibly, the observed sequence effects can be related to the effect of task-irrelevant stimulus repetitions on the number of task repetitions as observed in Demanet et al. (in press). Together with the present results, these effects suggest that a task repetition in VTS can be primed by repetitions of events in the environment. The finding that the sequence effects in the present study were not modulated by the alignment of the responses supports this conclusion and suggests that the sequence effects were not caused by temporary associations between task-selection and task-execution responses (e.g. Elsner & Hommel, 2004).

Regarding the impact of the length of the SPI on the strength of the sequence effects, the results of both experiments were less consistent. While SPI did not modulate the sequence effects when manipulated as a within-subjects factor in Experiment 1, SPI had a strong impact when it was manipulated as a between-subjects factor in Experiment 2. This finding indicates that the size of the sequence effects can depend on the use of strategies (Poulton, 1982). When SPI is always very short (SPI-50, Experiment 2), the efficiency of top-down control is reduced and the sequence effects are strong[4]. When SPI is always long (SPI-1,500, Experiment 2) top-down control is very efficient and contributes strongly to task selection and the sequence effects are counteracted. The observation that SPI had no influence on the sequence effects in Experiment 1 and that these effects were relatively small compared to the SPI-50ms condition in Experiment 2, implies that when the length of SPI is unpredictable, subjects invest more top-down control for voluntary task selection independent of the SPI. In other words, in Experiment 1, the strategy to select tasks intentionally and to avoid sequence effects seems to transfer from the SPI-1,500ms condition to the other conditions. In general, these findings clearly indicate that the relative contribution of top-down control and external factors in task selection can depend on strategic modulations.

In both experiments, we also found a substantial task-repetition bias which reduces with longer SPIs. This is consistent with previous studies of VTS (Arrington & Logan, 2004; 2005), and supports the idea that top-down processes are necessary to overcome the tendency the repeat tasks (e.g. Vandamme, Szmalec, Liefooghe & Vandierendonck, in press). Surprisingly, we observed that more tasks were repeated when preceded by task switches than by task repetitions. In other words, this indicates that people seem to

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[4] We also investigated the possibility that the stronger sequence effects in the SPI-50 condition in Experiment 2 were caused by the fact that the SPI on trial *n-1* was always 50ms and that therefore the idea of a repetition was more accentuated than in Experiment 1. An extra analysis indicated that the length of the SPI on trial *n-1* did not affect the size of the sequence effects in Experiment 1, $F<1$, which disconfirms this hypothesis.

avoid switching two trials in a row. Possibly, this finding can be related with the findings of Lien and Ruthruff (2008). Recently, they observed that when subjects were asked to switch voluntarily between three tasks they have a reluctance of switching back to the recently disengaged task (i.e., there were fewer ABA sequences than ABC sequences). These authors argued that this effect was due to persisting task-set inhibition, also called backward inhibition (e.g. Mayr & Keele, 2000). Possibly, the tendency to avoid two consecutive task switches in the present study could also be due to this persisting inhibition.

However, in a recent study of Vandierendonck, Demanet, Liefooghe, and Verbruggen (submitted) a model was developed that suggests that task selection depends on automatic retrieval of chains of task information from long-term memory. In this study, it was found that the repetition bias and the avoidance to switch two times in a row depends on the way task sequences are stored in and retrieved from long-term memory and not on persisting task-set inhibition.

To conclude, our results support the idea that a voluntary task choice, even in a double-registration procedure is never truly voluntary but is always the result of an interaction between bottom-up influences and top-down processes. Information in the environment guide a task choice, but this influence can be overruled by top-down control (Arrington, 2008; Ach, 1910/2006). The present study also indicates that the efficiency of these top-down processes to counteract bottom-up influences can be modulated by the use of strategies.

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APPENDIX A

For reasons of completeness we briefly report the results concerning the task-execution responses of Experiment 1. In the RT analysis, only trials on which a task was selected, correct trials and trials following correctly selected and executed trials were considered. In analogy with the analysis of the selection proportions, the trials with stimulus repetitions were excluded. This resulted in a loss of 26.2% of the trials. RTs were analyzed by means of a 2 (alignment: horizontal vs. orthogonal) by 2 (task transition: task repetition vs. task switch) by 2 (response transition: response repetition vs. response alternation) mixed MANOVA with repeated measures on the last two factors. We found a significant main effect of task transition, $F(1,38)=46.73$, $p<.01$, $\eta_p^2= .55$. Task switches (M=731ms, SE=22) were slower than task repetitions (M=632ms, SE=14). The effect of response transition was reliable, response repetitions were slower (M=689ms, SE=17) than response alternations (M=674ms, SE=17), $F(1,38)=13.87$, $p<.01$, $\eta_p^2=$ .27. Task transition interacted with response transition, $F(1,38)=69.84$, $p<.01$, $\eta_p^2= .65$. Switch costs were higher on response repetitions than on response alternations, and on task repetitions a response-repetition advantage was observed which transformed into a task-alternation advantage on a task switch (Table A1). Other effects were not significant.

For the error rates, only trials on which a task was selected and trials following correctly selected and executed trials were considered. Error rates were analyzed in a similar way. More errors were made during task switches (M=8.8%, SE=.9) than during task repetitions (M=6.6%, SE=.7), represented in a reliable effect of task transition, $F(1,38)=22.98$, $p<.01$, $\eta_p^2=$ .38. Also the effect of response transition was reliable, $F(1,38)=68.14$, $p<.01$, $\eta_p^2= .64$. More errors were made on response repetitions (M=9.3%, SE=.8) than on response alternations (M=6.1%, SE=.7). The interaction between task transition and response transition was significant, $F(1,38)=20.83$, $p<.01$, $\eta_p^2= .35$. Planned comparisons showed a disadvantage of response transitions on task switches, $F(1,38)=55.15$, $p<.01$,

η_p^2= .59, and an advantage on task repetitions, $F(1,38)=10.36, p<.01$, η_p^2= .21. No other effect or interaction was reliable.

Table A1: Task-execution RTs and Error Rates as a function of response alignment, response transition and task transition for Experiment 1. Standard Errors are presented in *Italic.*

	Horizontal Alignment				**Orthogonal Alignment**			
	Response Repetition		Response Alternation		Response Repetition		Response Alternation	
	RT	Error	RT	Error	RT	Error	RT	Error
Task	608	8.5	625	6.9	633	6.1	662	5.1
Repetition	*18*	*1.0*	*20*	*1.0*	*18*	*1.0*	*20*	*1.0*
Task	765	13.0	703	7.8	750	9.6	706	4.8
Switch	*33*	*1.5*	*30*	*1.2*	*33*	*1.5*	*30*	*1.2*

APPENDIX B

For Experiment 2, the same exclusion criteria were used for calculating RTs and error rates as in Experiment 1. This resulted in a loss of 28.8% of the trials. As in Experiment 1, task-execution RTs and error rates were analyzed to check for the effect of task transition and response transition on the task-execution responses itself. Task-execution RTs and error rates were analyzed by means of a 2 (alignment: horizontal vs. orthogonal) by 2 (task transition: task repetition vs. task switch) by 2 (response transition: response repetition vs. response alternation) mixed MANOVA with repeated measures on the last two factors. The RTs confirmed the significant effect of task transition, $F(1,78)=87.20$, $p<.01$, $\eta_p^2= .53$. Task switches (M=711ms, SE=14) were slower than task repetitions (M=626ms, SE=9). The interaction between task transition and response transition was reliable, $F(1,78)=29.71$, $p<.01$, $\eta_p^2= .28$. A response-repetition benefit when repeating a task changed into a response-alternation benefit when switching tasks (Table B1). This was confirmed through planned comparisons for task repetitions, $F(1,78)=10.89$, $p<.01$, $\eta_p^2= .12$, and task switches, $F(1,78)=20.86$, $p<.01$, $\eta_p^2= .21$. Also, the interaction between task transition and alignment was reliable, $F(1,78)=4.57$, $p=.04$, $\eta_p^2= .06$, showing that switch costs were higher with a horizontal than an orthogonal alignment. No other interactions were significant with the highest F-value for the interaction between response transition and alignment, $F<1$.

More errors were made on task switches (M=10.1%, SE=.7) than on task repetitions (M=7.5%, SE=.5), represented by a reliable main effect of task transition, $F(1,78)=34.86$, $p<.01$, $\eta_p^2= .31$. The interaction between task transition and alignment, $F(1,78)=3.87$, $p=.05$, $\eta_p^2= .05$, was marginally significant, indicating that the effect of task transition was stronger in the horizontal than in the orthogonal alignment (Table 2). The main effect of response transition was significant, $F(1,78)=40.18$, $p<.01$, $\eta_p^2= .34$; response repetitions (M=10.13%, SE=.6) were more error prone than response alternations (M=7.4%, SE=.7). The significant interaction between task transition and response transition, $F(1,78)=25.72$, $p<.01$, $\eta_p^2= .25$, shows a response-repetition disadvantage when switching tasks (Table B1) and no effect of response transition when repeating tasks. This was confirmed by planned comparisons on task repetitions, $F<1$, and task switches, $F(1,78)=50.55$, $p<.01$, $\eta_p^2= .39$. No other interactions were significant; highest F-value for the three-way interaction between task transition, response transition and alignment, $F<1$.

Table B1: Task-execution RTs and Error Rates as a function of response alignment, response transition and task transition for Experiment 2. Standard Errors are printed in *Italic*.

	Horizontal Alignment				**Orthogonal Alignment**			
	Response Repetition		Response Alternation		Response Repetition		Response Alternation	
	RT	Error	RT	Error	RT	Error	RT	Error
Task Repetition	629	7.6	644	7.1	606	7.5	625	7.6
	13	*.7*	*14*	*.9*	*13*	*.7*	*14*	*.9*
Task Switch	766	13.3	718	8.3	700	12.1	663	6.5
	21	*1.3*	*19*	*1.0*	*21*	*1.3*	*19*	*1.0*

CHAPTER 5
A CHAIN-RETRIEVAL MODEL FOR VOLUNTARY TASK SWITCHING

***Manuscript submitted for publication*[1]**

To account for the findings obtained in voluntary task switching, it was hypothesized that random task selection involves retrieval of task information from long-term memory, and that the retrieved information guides task selection and task execution. This was formalized in the chain-retrieval model, which is based on retrieval of acquired sequences of tasks from long-term memory. To test this model, sequences of tasks (magnitude and parity judgment) and the corresponding transition sequences (task repetitions or switches) were analyzed with the help of dependency statistics. Task sequences showed an immediate repetition bias followed by an alternation bias, whereas transition sequences only showed an immediate alternation bias. The model parameters were estimated on both task and transition sequences and these estimates were used to predict autocorrelations of tasks and transitions. The transition-based fit showed better correspondence to the data. Implications for our understanding of voluntary task selection and broader theoretical implications are discussed.

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INTRODUCTION

Goal-directed behavior relies on a determination to achieve the current goal, but is also adaptive to changes in the environment (e.g., Logan & Gordon, 2001; Norman & Shallice, 1986). Such changes may require a shift to another goal. The task-switching paradigm has been the preferred method to study such flexible changes in the laboratory (see Monsell, 2003, for a review). Many studies have shown that task switching comes with a cost, which has been attributed to task-set reconfiguration processes, interference, or both (e.g., Allport, Styles, & Hsieh, 1994; Mayr & Kliegl, 2000; Meiran, 1996, 2008; Rogers & Monsell, 1995; Waszak, Hommel, & Allport, 2003). It can be doubted, however, whether voluntary choices contribute much to the switch cost, because most procedures to study task switching are quite restrictive in this respect. These procedures typically instruct the subject when to repeat and when to switch. Behavioral flexibility, on the contrary, also involves the possibility to *choose* for a particular course of action or for a particular goal. In most task switching procedures, there is no room for such task-choice processes. The voluntary task switching (VTS) procedure (Arrington & Logan, 2004, 2005) is an exception. This specific procedure was designed to allow more ‘freedom’ in choosing or selecting a particular task or task goal by giving subjects the freedom to select and execute the task of their choice on every trial. This makes it an interesting procedure because it not only provides the usual task performance measures but also enables investigation of the processes involved in choosing or selecting a task to be performed.

Even though the theoretical importance of understanding the processes underlying voluntary choice of courses of action is undisputed, thus far not so much is known about these processes. Previous research using the VTS procedure has shown that people tend to repeat the same task more often than expected on the basis of chance (Arrington & Logan, 2004), and that this tendency becomes stronger when the response-stimulus interval (RSI) is shorter (Arrington & Logan, 2005). These findings suggest that choosing to perform a task depends on endogenous task selection (see e.g., Arrington & Logan, 2005; Arrington & Yates, 2009; Liefooghe, Demanet, & Vandierendonck, 2009). However, bottom-up factors also seem to play a role as it was shown that task choice is affected by repetition priming (Mayr & Bell, 2006), stimulus availability (Arrington, 2008), and processing efficiency (Arrington & Rhodes, In press). Furthermore, the presence of a working memory load increases the task-repetition bias in the presence of bottom-up factors such as stimulus repetitions, repetitions of irrelevant events and stimulus-task associations (Demanet, Verbruggen, Liefooghe, & Vandierendonck, in press).

The present study aims to contribute to our understanding of the processes involved in task choice by elaborating and testing a model of task-choice processes as they occur in VTS. The instructions typically used in VTS experiments impose a constraint on task selection by stressing that both tasks must be executed about equally often and in random order. As similar instructions have been used in previous research on random generation, it seems straightforward to expect similar behavior in both situations and to hypothesize that the processes underlying generating random series of events and random series of tasks are the same. Yet, there is a clear difference in choice behavior between the two kinds of procedure both in terms of the tasks imposed on the subjects and in terms of the processes involved. Random task selection in VTS consistently shows a tendency to repeat the same task more often than expected on the basis of chance, whereas random generation of events reveals an alternation bias, i.e. a tendency to alternate too often between two events and to produce too short runs of repetitions of the same event (Lopes, 1982; Lopes & Oden, 1987; Neuringer & Allen, 1986; Rapoport & Budescu, 1992; Treisman & Faulkner, 1987; Wagenaar, 1972).

Given the fact that the choice instructions used in VTS and in random generation are the same, and the hypothesis that the generation process is the same in both task settings, there must be other important differences between both settings that can account for these distinctive patterns. The most important difference is that in traditional random generation tasks, the goal is to generate series of random events, whereas in VTS, the randomly selected tasks must also be executed. This difference has two consequences. First, by executing the tasks, events that are external to the process of task generation, such as repetition priming, may directly interfere with the process of random generation. As was already mentioned, in VTS more task repetitions are selected under conditions with repetition priming (Mayr & Bell, 2006) and this effect is enhanced when top-down control is less efficient by imposing a working memory load (Demanet et al., in press). Second, the task selected may have an effect on performance. More in particular, one task may be experienced as being much easier than another one, which in turn may affect the decision to repeat the task or to switch to the other task (Liefooghe, Demanet, & Vandierendonck, in press). Third, it is well known from research on task switching that task repetitions are much easier than task switches, and this is also the case in VTS (e.g., Arrington & Logan, 2005). Accordingly, subjects may experience that repetitions go easier than switches and may thus prefer task repetitions over task switches.

As an interim conclusion, it seems fair to say that random generation and random task selection both involve random selection. In VTS, the context in which these random selection processes occur, differs in important ways. Understanding the processes underlying task choice in VTS thus requires the elaboration of models of random generation that meet the additional task settings imposed by VTS. Accordingly, the present study aims to elaborate the hypotheses about the processes underlying task choice in VTS. The method used to achieve this goal consists of the development of a model of random task generation that allows the result of the generation to be changed by external events. These models will be compared with other models of random generation by applying the models to the data of a VTS experiment.

MODELING TASK SELECTION PROCESSES

The long standing tradition of research in human random generation has already shown that sequences of events generated by humans show robust deviations from a model of statistical independence (e.g., the Bernoulli model). For example, generated sequences of coin tosses deviate from independence by the presence of an alternation bias, as already mentioned. Models of human random generation have tried to account for this in different ways.

A first approach to account for statistical dependence uses Markov-type models. The model of Budescu (1987) and some related models have been proposed to specifically predict statistical dependence in the form of perseveration (i.e., repetition bias) and alternation (Vandierendonck, 2000a). Although such models— in particular those that can predict perseverations— could be useful to describe what goes on in VTS, it will become clear later in this article that these models are insufficient to account for task choice processes. It seems likely that task choice in VTS depends on several factors for which a more elaborate model is needed.

A second approach that has been followed is exemplified in the model developed by Rapoport and Budescu (1997). According to this model, events are generated while a monitoring process follows within a window of a particular width whether the generated sequence looks random. When the monitoring process detects a deviation from this subjective idea of randomness, the next event will be selected so that randomness is restored within the window. This model provides an excellently fitting description of human random generation behavior. Application of the model of Rapoport and Budescu to task choice in VTS leads to some difficulties, though. For one thing, the model predicts a tendency to alternate, whereas task choice in VTS is characterized by a tendency to repeat. Under the hypothesis that external occurrences occasionally provoke task repetitions, a task repetition bias could ensue. However, the monitoring mechanism will detect such occurrences as deviations from the person’s randomness conception, and this will result in corrective action so that in the end an alternation tendency will still be present. In other words, even though bottom-up events could occur, monitoring and subsequent correction will still result in an alternation bias. Clearly, the problem arises because the monitoring mechanism of the model inspects retrospectively the recent part of the sequence; with a proactive mechanism this difficulty could be avoided.

In what follows, we describe a model of task selection in VTS. For such a modeling effort to be successful, it should take into account results from earlier studies of random generation as well as results from studies of VTS.

MODELING ASSUMPTIONS

The proposed model builds on the hypothesis that random task selection in VTS and random generation are based on a common mechanism. The subjective notion of randomness as specified in the model of Rapoport and Budescu (1997) is taken as a sufficient basis for generating random sequences with an alternation bias. We further adopt the hypotheses that (1) task performance difficulty affects the outcomes of the random generation mechanism and (2) that bottom-up events such as repetition priming (Mayr & Bell, 2006) intrude into the outcome of random generation such that cognitive control does not efficiently block these intrusions (Demanet et al., in press). We first elaborate the processes involved in random generation and subsequently describe how the outcome of this process can be modified in VTS.

For the instantiation of the random generation mechanism, we propose that the selected tasks are retrieved from long-term memory (cf. Baddeley, 1996). More specifically, we propose that tasks are retrieved from long-term memory (LTM) in chunks (or strings of tasks), so that task selection is based on a retrieval of the task name from LTM (cf. Schneider & Logan, 2007), and that associative chaining or chunking of task names occurs. During the initial phases of the experiment, task chunks such as BAA, BAB and BBA are formed and become more strongly associated with practice. Having just executed task A, this event will prime chunks that start with an A, and so chains such as ABB, ABA and AAB may become active.

The chains that are formed and applied during the experimental session may be biased by a number of factors. First, we assume that the instruction to be random imposes a restriction, so that chains with too many repetitions will be avoided (as in the model of Rapoport & Budescu, 1997). This will result in storing and strengthening chains such as ABBAB rather than ABBBB, and this effect may be amplified by feedback that is presented during the training phase with the aim of ensuring that the instructions are followed. Second, we assume that the instruction that both tasks must occur approximately an equal number of times will result in strengthening of sequences that do not violate this balance. This results in a preference for sequences such as ABBAA and ABBAB over AABAA and ABBBB. Third, we also assume that the application of the generated chain of tasks to the targets may have implications for preferences among chains (e.g., Liefooghe et al., in press). As already explained, the experience of the difference in difficulty between task switches and task repetitions may bias the selection towards chains with more repetitions, which would lead to a preference of chains like AAABB over AABAB. Fourth, we assume that the size of the chains is constrained by working memory capacity. As a retrieved chain has to be maintained in short-term memory during a number of trials, the maximal length of a chain will normally be within working memory capacity. Even though the chain may be coded as an entity (a chunk), it is important to keep track of the progress when the chain is applied and this necessitates a decoding of the chunk.

MODEL ELABORATION

These assumptions are now elaborated in a formal model. We will define three parameters, *m, p,* and *r,* that express quantitatively the operation of underlying processes.

The first parameter, *m*, is related to working memory capacity and specifies the maximal length of the chains retrieved from LTM[2]. We assume that the minimum length is 3. Of course, chains of two elements are possible, but chains of this length do not allow enough variability: only AB and BA are balanced sequences, and because such sequences do not contain repetitions, a repetition bias based on experience with the easier repetitions cannot develop. Therefore, we adopted 3 as the lower limit. Table 1 displays the sequences that are possible at each of the lengths 3-6. The sequences considered are balanced in the sense that the two tasks occur $m/2$ times in the sequences with an even length and occur minimally $m/2$ times and maximally $m/2+1$ times in odd numbered sequences (this is similar to the procedure used by Logan, 2004, in the task span procedure). This way, both tasks will be selected approximately equally often. At the same time, also the requirement of randomness is realized because all the sequences in the table are those that are usually judged as looking random (see also Rapoport & Budescu, 1997) as these sequences show, on average, a tendency to alternate, which is shown in Table 1 in the column labeled '# Rep'.

[2] In view of the considerations that have led us to the concept of chains of task names, it is likely that the actual size of the chains would increase during the initial practice session and further on through the experimental session. However, because of lack of information about this hypothesized process and about the development of the changes through a session, we make the simplified assumption that m is constant throughout the experiment and takes a value between 3 and 6.

Table 1. Overview of the balanced sequences of tasks A and B that are possible at lengths 3-6. The corresponding sequences of transitions (R = repetition; S = switch) are also displayed as well as the number of repetitions in the sequence.

Length 3			**Length 4**		
Tasks	Transitions	# Rep	Tasks	Transitions	# Rep
AAB	RS	1	AABB	RSR	2
ABB	SR	1	ABBA	SRS	1
ABA	SS	0	ABAB	SSS	0
Length 5			**Length 6**		
Tasks	Transitions	# Rep	Tasks	Transitions	# Rep
AAABB	RRSR	3	AAABBB	RRSRR	4
AABBB	RSRR	3	AABBBA	RSRRS	3
AABBA	RSRS	2	AABBAB	RSRSS	2
AABAB	RSSS	1	AABABB	RSSSR	2
ABBBA	SRRS	2	ABBBAA	ARRSR	3
ABBAA	SRSR	2	ABBAAB	SRSRS	2
ABBAB	SRSS	1	ABBABA	SRSSS	1
ABABB	SSSR	1	ABAABB	SSRSR	2
ABAAB	SSRS	1	ABABBA	SSSRS	1
ABABA	SSSS	0	ABABAB	SSSSS	0

The second parameter, *p*, is related to the strength of a chain. We assume that all the sequences of a particular length *m* (as presented in Table 1) are stored in LTM. In order to model the variability in the retrieval of chains, each chain is supposed to have a strength that determines its likelihood of being retrieved. This likelihood depends on the value of a parameter *p*, which is the probability of a repetition in the stored sequence (1 - *p* is the probability of a switch). The larger the value of *p*, the larger will be the probability of selecting a chain that contains one or more repetitions. In other words, *p* represents a bias towards more repetitions. This way, the consideration is implemented that experience with execution of the tasks (repetitions are easier than switches) will influence the retrieval of task chunks. The parameter *p* can now be used to define the strength of each chain as $w = p^R(1-p)^S$, where *w* is the weight or strength of the chain and *R* and *S* are respectively the numbers of repetitions and switches in the chain. The sequence AABB, for example, contains two repetitions and one switch: thus $w = p^2(1-p)$. Let W be the sum of the weights *w* of all the sequences in the set, the probability to select a particular sequence *i* with weight w_i is then w_i / W.

The third parameter, *r*, is related to bottom-up priming. We assume that with a probability *r* an event occurs that triggers an action intruding at this particular point in the sequence. We assume that the *r* parameter could account for the task-repetition bias typically observed in VTS[3]. Several choices as to what happens with the already selected chain are possible; in the present model, execution of the retrieved chain continues after the

[3] Even though the *p* parameter may also lead to more repetitions, its efficiency in this respect is limited in that a value of p above 0.5 only helps to select chains with more repetitions. The intrusions that occur with probability *r* add additional repetitions to the generated sequence.

intrusion. The importance of this choice will be addressed in the General Discussion.

Thus far this *chain-retrieval model* specifies that short balanced sequences (chains) avoiding too many repetitions are stored in memory and have a strength that determines the probability of being selected. However, Table 1 indicates that the pool of chains defined this way is biased towards alternations, whereas previous findings suggest a repetition bias in VTS. We can account for the latter finding in two ways. First, experience with task difficulty will lead to a preference (parameter *p*) for chunks with more repetitions (Liefooghe et al., in press). A second way to achieve more task repetitions is by assuming that bottom-up intrusions will occur (with a probability *r*) in the form of task repetitions. This is in line with the nature of the bottom-up events reported in the literature (Demanet et al., in press; Mayr & Bell, 2006).

The description above focused on how the retrieval of individual chains is modeled. Two further issues must be decided, namely the content of the chains and how the chains are coupled to form a continuous sequence. First, we deal with the issue as to how the individual chains are linked together to produce fluent behavior over a longer run of trials. The most straightforward way is to simply concatenate the retrieved chains. However, a simple concatenation, such as AABB followed by ABAB will create an additional transition at the point of linking (AABB**A**BAB). In some cases, this will be a switch, in other cases a repetition. Because this coupling method creates unpredictable events, it is not very useful as a mechanism in a formal model. Therefore, another way of coupling task chains is needed. It seems plausible that the last task performed primes the start of the next chain (e.g., Baddeley, Emslie, Kolodny, & Duncan, 1998), so that the next retrieved chain will start with the same task that ended the chain. The spurious transition that occurs in concatenation can now be avoided by assuming that the chains are merged, so that the common task at the junction is selected only once. Given the selected chains ABBA and AABB, the connected sequence will be ABB(A)ABB, where the A between parentheses shows the merging of the two events. This will result in three repetitions and three switches, without inserting additional transitions.

The second issue we need to address is the content of the chunks in LTM. It seems natural to suppose that the chains learned and stored in LTM are chains of task names. Recent evidence from registration of event-related potentials in VTS (Vandamme, Szmalec, Liefooghe, & Vandierendonck, in press) suggests that subjects have a bias to repeat the previous task, overruling this bias on switch trials. This could indicate that transitions rather than tasks are selected. Also in the model proposed here, information about the difficulty of the *transitions* is needed for the selection of chains with more easy transitions (repetitions). Another argument in support of this idea is that in a task-switching context, subjects will quickly learn that they have to repeat the task or that they have to switch to the other task. By storing chains of transitions, the chain contains the information which is relevant for preparation for the upcoming task. A third argument is that after retrieval of the transition chain, the load on working memory is smaller because a chain of transitions contains less events than an equivalent chain of tasks.

In view of all these arguments, it could be decided to develop two versions of the model, one where the chains contain task names and another version where the chains contain transitions. In comparison with the version where the chains contain tasks, for the version where chains contain transitions it is useful to assume that the chains are simply concatenated and not merged. This is because simple concatenation of the retrieved chains of transitions would not result in a sequence in which extra transitions are added. For example, concatenation of RSR to SSS results in RSRSSS, which contains exactly the same transitions as the component chains. Even though, it is on a theoretical level possible to distinguish the two versions of the chain-retrieval model, they share the same parameters so that an empirical distinction between these versions is not easy to obtain. However, because the model based on task chains produces sequences of task choices, it predicts sequences of tasks, whereas the model based on transition chains predicts sequences of transitions. This provides the possibility to test the model in two ways, namely by fitting the model to sequences of tasks and by fitting it to sequences of transitions. In view of all this, we focus on only one possibility, namely the chain-retrieval model; it will be tested twice, once on tasks and once on transitions.

In sum, the formalization developed in the previous paragraphs specifies a number of constraints on the psychological processes expressed in the three free parameters (m, p, r). This description of the model suggests it is possible to build similar models with slightly different assumptions. Appendices A and B contain an overview of other possibilities and how they fare when used to fit actual data. As all these variations result in poorer fits and/or predictions, we do not consider them in the main text. In the next sections, we apply the model to choice data obtained in an experiment. First, we describe the experiment and its results. Next, we apply the model to these data.

EXPERIMENT

In this section, we report the results of an investigation of task selections in VTS. In order to obtain task selections which are maximally independent of task execution, we used the double-registration procedure described by Arrington and Logan (2005, Exp. 6). In this procedure, each trial consists of two parts. First, a probe (‘?’) is presented, instructing the subjects to indicate which task they will perform. Second, a stimulus is presented, to which the selected task must be applied. Only the first response (task indication) is of interest in the present context.

METHOD

Subjects

Eighty first-year psychology students at Ghent University participated for course requirements and credit. All subjects had normal or corrected-to-normal vision, were right-handed, and all were naïve to the purpose of the experiment. Subjects were randomly assigned to two conditions (forty subjects per condition) that differed in the stimulus onset asynchrony (SOA) of the stimulus and the probe (see below).

Materials

Stimuli were the digits 1-9, excluding 5. Subjects were required to classify the digits either on the basis of their magnitude (smaller or larger than five) or their parity (odd or even). Responses were registered by means of the numeric pad of a standard keyboard. One hand was used for pressing the task-selection keys; the other hand was used for pressing the task-execution keys.

Procedure

Although we only need the task-selection data, we describe the complete procedure of data collection, which served other purposes that are not relevant to the present endeavor (Demanet, Liefooghe, Vandierendonck, & Verbruggen, under revision). Pentium III personal computers with a 17-inch color monitor running the Tscope C/C++ library (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006) were used. Each session lasted for approximately 45 minutes. After subjects signed an informed consent, instructions were presented on screen and paraphrased if necessary. The instructions concerning unpredictability of voluntary task switches were the same as those used by Arrington and Logan (2005), namely that each task should be performed about equally often and that the sequence should form a random order as in coin tossing.

On each trial, a probe (‘?’) was presented in a square 5 mm above the centre of the screen. This probe disappeared when subjects pressed one of the task-selection keys. This was followed 400 ms later by the appearance of the target stimulus, 5 mm below the centre of the screen. The target remained on screen until subjects responded on the basis of the previously selected task or until a maximal response time of 2,500 ms elapsed. The probe of trial n appeared either 50 ms (short SOA condition) or 1,500 ms (long SOA condition) after the presentation of the stimulus of trial *n-1*.

After two practice blocks of 64 trials, subjects performed two experimental blocks of 256 trials. In the first practice block, the emphasis was on familiarization of the procedure of selecting and executing the different tasks. In the second practice block, the emphasis was on random generation of the tasks. In order to increase subjects awareness of their selection behavior, the warning ‘do not forget to switch tasks’ was shown for 1000 ms whenever the subjects selected the same task four times in a row. When the subjects switched between tasks four times in a row, the warning ‘do not forget to repeat tasks’ appeared for 1,000 ms. This task-selection feedback was presented in the second practice block only.

During the entire experiment, subjects received on-line feedback about their performance. A red screen appeared for 50 ms when they made an error on the target. When they were too slow to select a task (RT > 2,500 ms), the message ‘no task selected’ was displayed for 1,500 ms. Following each block (practice and experimental), a general summary about the performance during that block was shown. This feedback included the mean reaction times on the targets, the percentage of errors, the selection percentage of each task, the percentage of failures to select a task, and the percentage of task repetitions and task switches. If necessary, subjects were corrected: they were urged to switch more or to repeat more when the proportion of repetitions or switches was above .70, to make fewer errors when percentage of errors was above 15%, to respond faster when mean task-execution reaction time was above 1,200 ms or when the proportion of trials without a task-indication response was above 10%, and to be more random when they selected a particular task on more than 75% of the trials.

Data analysis

The analysis focuses on the series of task choices and task transitions. Such sequences of random events are often summarized by using a runs statistic, which yields a proportion of the runs of the same event at a series of lengths. As the task choices and the transitions within the sequence of tasks are binary events, the sequence of events can be expressed as a series of binary digits (0 or 1). A sequence of tasks is a series of task names; using the letters M (magnitude judgment) and P (parity judgment), an example of a series of selected tasks may be MMPMPPM. Similarly, the letters R (repetition) and S (switch) can be used to describe a sequence of transitions. To convert the sequence to binary values, M can be recoded as 1 and P as 0 (or vice versa) and R can be coded as 1 and S as 0 (or vice versa).

The runs statistic (Sternberg, 1959a; Vandierendonck, 2000a), can be defined as follows

$$r_k = \frac{1}{N-k+1} \sum_{i=1}^{N-k+1} x_i x_{i+1} \dots x_{i+k-1} \quad (1),$$

where N is the number of events in the complete sequence and r_k is the proportion of runs with length k in which $x_k = 1$. Consider a sequence like '0110111010100011', where the target outcome is coded 1. The number of runs of length 1 equals the number of 1s in the sequence, which is 9 (code 1 occurs 9 times). Runs of length 2 consist of two consecutive 1s; there are four such groups of 1s in the sequence. Runs of length 3 consist of three consecutive 1s; there is only one such group. By dividing these counts by the number of possible runs of a particular length, a proportion is obtained for each length. Although the runs statistic captures deviations from independence, it is not particularly sensitive in detecting very small deviations from independence because the values become smaller as the run length increases (see example). However, the statistic is useful because it captures deviations from statistical independence in both directions: when there are more repetitions, there will be fewer short and more long runs, and when there are more alternations, the opposite pattern will occur (relatively more short and fewer long runs).

In addition to the runs statistic, we used the *autocorrelation statistic* (Sternberg, 1959a; Vandierendonck, 2000a), which is very sensitive to deviations from independence, and therefore useful to make a more fine-grained analysis of the data. This statistic expresses the tendency for pairs of events in the sequence to correlate with each other. The pairs of events that are considered can be close together or further apart (short or long lag).

The autocorrelation statistic lag k (c_k) is defined as

$$c_k = \frac{1}{N-k} \sum_{i=1}^{N-k} x_i x_{i+k} \qquad (2),$$

The correlation expresses the probability that both elements in the pair (separated by lag k) are the same. When lag is 1, for example, the autocorrelation expresses the probability that the current event is the same as the previous one. Considering the example we had before '0110111010100011', the autocorrelation lag 1 looks at all occurrences of two consecutive 1s; there are 4 of these. Actually, by definition this is the same as runs of length 2. The autocorrelation lag 2 looks at two occurrences of a 1 separated by another (not relevant) outcome. The triplets to consider are 011, 110, 101, 011, 111, 110, 101, 010, 101, 010, 100, 000, 001, 011 and there are only four cases out of these 14 where the first and the third element are both 1. The autocorrelation statistic is a measure that is sensitive to statistical dependencies based on learning to repeat an event: the autocorrelation will tend to be larger when a learning process governs the production of the events in the series (Sternberg, 1959a, 1959b). Application of the statistic requires that one task is coded 1 and the other 0. By applying the statistic twice to the sequence of task choices, once with Magnitude coded as 1 (Parity 0) and once with Parity coded as 1 (Magnitude 0), the joint outcome specifies all correlations in the data. This joint outcome is complementary to all tendencies to alternate instead of to repeat. Hence, the statistic applied in this way is sufficient to describe all deviations from independence.

RESULTS

The entire data analysis will be performed in two steps. In the first step, the analysis focuses on the sequence of task choices; in the second step, on sequences of transitions. The analyses of the runs and the autocorrelation statistic are reported separately. Each statistic is calculated on the task sequence with magnitude coded as 1 and a second time with parity code as 1. The average of these two calculations is entered into the analysis.

Focus on tasks

For the magnitude task, the 2 x 256 task selections of each subject were coded 1 when magnitude was selected and 0 otherwise (parity or no selection). Similarly, for the parity task, the selections were coded 1 when parity was selected and 0 otherwise. About 1% of the trials were non-selections. Due to the coding, non-selections did not contribute to the run length or the autocorrelation data.

These data were used to calculate the proportion of runs of lengths 1-10 and autocorrelations at lags 1-10. Per statistic, the multivariate general linear model was applied to the data on the basis of a 2 (SOA: 50 or 1,500 ms) x 2 (Task: magnitude vs. parity) x 10 (Lengths or Lags) factorial design with repeated measures on the last two factors. For all analyses, $\alpha = .05$, unless otherwise mentioned. In order not to overload the report with an enumeration of statistical tests, the outcomes of the complete analyses are presented in Table 2; only the effects that are central to our main purpose are reported in the text.

Table 2. Results of the analyses of variance of the proportions of runs and autocorrelations in the task-based analysis on the basis of a 2 (SOA: 50 vs 1,500 ms) × 2 (Task: magnitude vs parity) × 10 (Lengths/Lags 1-10) factorial design with repeated measures on the last two factors.

		Runs			**Autocorrelations**		
Effect	df	*F*		η_p^2	*F*		η_p^2
SOA (S)	1,78	8.2	**	.09	1.0		.01
Task (T)	1,78	34.1	***	.30	40.2	***	.34
Lag (L)	9,70	7108.6	***	1.00	27.0	***	.78
T x L	9,70	4.6	***	.37	.6		.07
S x T	1,78	3.1		.04	.7		.01
S x L	9,70	2.0	†	.20	1.5		.16
S x T x L	9,70	1.6		.17	1.0		.12

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; † $p = .051$

Runs. Figure 1 (top) displays the runs proportions as a function of task, run length and SOA. On average, the selection proportions of magnitude and parity were 0.48 and 0.51 respectively. As can be seen in Table 2, run proportions depended on task, length, and SOA. Proportions of runs were higher for the parity task (M = .13) than for the magnitude task (M = .11), and they decreased with run length. Run proportions were smaller when SOA was long (.10 for long versus .13 for short SOA). Length interacted with task and with SOA. The drop in the proportions was less steep for the parity task and for short SOA. This shows that there was a tendency to repeat the parity task more than the magnitude task and also a tendency to repeat tasks more at short than at long SOA.

Autocorrelations. The autocorrelations are shown in Figure 1 (bottom) as a function of task, lag and SOA. Only the effects of task and lag were reliable (see Table 2). Figure 1 shows that the correlations start high and then quickly drop off and stabilize from lag 5 on. Overall, autocorrelations were lower in lags 2-4 (M = .22) than in lags 7-9 (M = .24), $F(1,78) = 23.76$, $\eta_p^2 = 0.23$. This contrast interacted with SOA, $F(1,78) = 6.47$, $\eta_p^2 = 0.08$. The contrast was smaller at short (.22 vs. .23) than at long SOA (.21 vs. .25). These findings show that there is a rather strong repetition tendency (autocorrelation) at lag 1, but that in lags 2-4, the autocorrelation is rather weak. This suggests that a tendency to immediately repeat the task is soon followed by one or more switches.

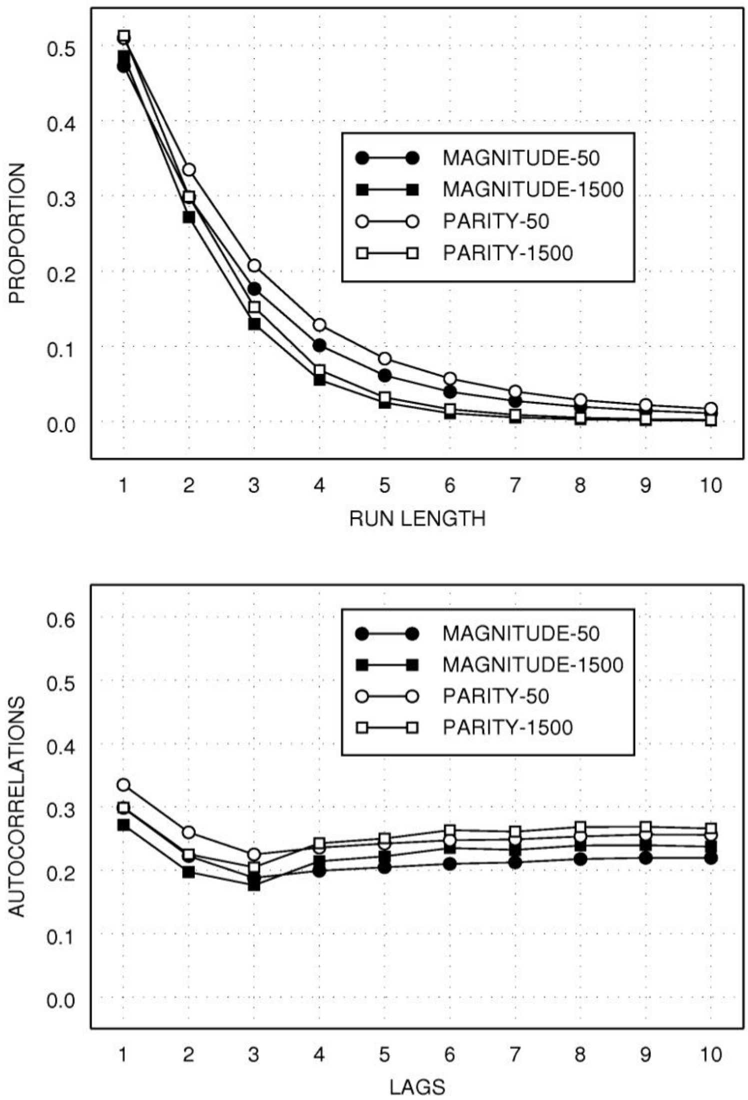

Figure 2. Transition-based analysis of task choices. Top Panel: Proportion of runs length 1-10 as a function of SOA (50 vs. 1,500 ms) and transition (repetition vs. switch). More frequent and longer runs of repetitions occur in the short SOA condition. Bottom Panel: Proportions of autocorrelations lag 1-10 as a function of SOA (50 vs. 1,500 ms) and transition (repetition vs. switch). At lag 1 the proportion of correlations is lower than at the later lags, where it is quite stable. Correlations are higher for repetitions especially at short SOA.

Focus on transitions

In the sequential analysis of the transitions, repeating the same task was coded 1 and changing the task or failing to select a task was coded 0; in the calculation targeting on switches, changing tasks was coded 1 and repeating the same task or failing to select a task was coded 0. In all other respects, the same data-analytic method was used as for the analysis focusing on task selections. The statistical analyses are reported in Table 3.

Runs. Transition runs are shown in Figure 2 (top) as a function of transition, length and SOA. Clearly, runs of repetitions (*M* = 0.14) were more frequent than runs of switches (*M* = 0.07) at all lengths[4]. Run proportions were only slightly longer on short (*M* = 0.103) than on long SOA (*M* = 0.102). All interactions were reliable (see Table 3). The dominant presence of repetitions confirms the repetition bias at the level of tasks. Repetitions were repeated more often than switches especially at short SOA.

Autocorrelations. Figure 2 (bottom) displays the transition-based autocorrelations as a function of transition, lag and SOA. In contrast with the task-based autocorrelations, the transition-based autocorrelations seem quite stable, except at lag 1. Lag correlations were larger for repetitions (*M* = .38) than for switches (*M* = .17). They also varied over lags. In particular, correlations were lower at lag 1 (*M* = .22) than at other lags (*M* = .28), $F(1,78) = 146.54$, $\eta_p^2 = 0.65$. This contrast explains most of the variance among the means per lag: $r^2 = .98$. Transition and lag interacted, which basically corresponds to an interaction of transition with the contrast between lag 1 and lags 2-10, $F(1,78) = 72.20$, $\eta_p^2 = 0.48$. Transition was also involved in an interaction with SOA, as displayed in Figure 2. Finally, the

[4] Proportions of repetitions and switches are inversely proportional. For this reason they should not be entered together in an ANOVA. This does not apply to proportions of runs of repetitions and switches.

triple interaction of SOA, transition and lag was also significant. Repetitions are selected more often than switches and therefore repetitions also tend to be repeated more than switches. However, for both, repetitions and switches, this tendency is smaller at lag 1 than at longer lags, where transitions rather show a pattern of independence, but repetitions are still repeated more than switches.

Table 3. Results of the analyses of variance of the proportions of runs and autocorrelations in the transition-based analysis on the basis of a 2 (SOA: 50 vs. 1,500 ms) × 2 (Tasks: magnitude vs. parity) × 10 (Lengths/Lags 1-10) factorial design with repeated measures on the last two factors.

		Runs			**Autocorrelations**		
Effect	df	*F*		η_p^2	*F*		η_p^2
SOA (S)	1,78	4.4	*	.05	2.8		.03
Trans(T)	1,78	26.8	***	.26	55.1	***	.41
Lag (L)	9,70	9424.5	***	1.00	20.5	***	.72
T x L	9,70	37.9	***	.83	9.25	***	.54
S x T	1,78	8.5	**	.10	6.1	*	.07
S x L	9,70	2.2	*	.22	1.3		.14
S x T x L	9,70	6.5	***	.46	5.4	***	.41

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

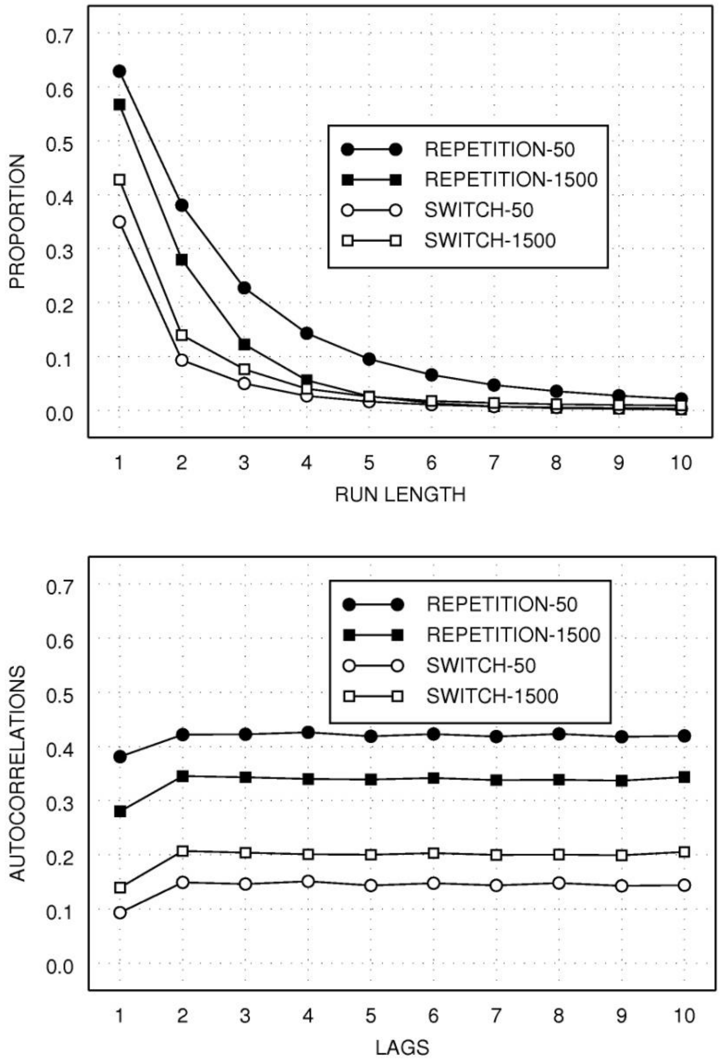

Figure 2. Transition-based analysis of task choices. Top Panel: Proportion of runs length 1-10 as a function of SOA (50 vs. 1,500 ms) and transition (repetition vs. switch). More frequent and longer runs of repetitions occur in the short SOA condition. Bottom Panel: Proportions of autocorrelations lag 1-10 as a function of SOA (50 vs. 1,500 ms) and transition (repetition vs. switch). At lag 1 the proportion of correlations is lower than at the later lags, where it is quite stable. Correlations are higher for repetitions especially at short SOA.

Discussion

The task-based analysis revealed that both the proportions of runs of lengths 1-10 and the autocorrelations lag 1-10 depended on task and on SOA. An immediate task repetition bias was followed by more alternations in the lag 2-4 window and by a stabilization of the autocorrelation from lags 5-6 on. Thus, the task-repetition bias reported in the literature (Arrington & Logan, 2004, 2005) was confirmed, but the present study showed that this bias is rather a local effect mainly present at lag 1. The presence of more alternations in lags 2-4 is consistent with the observation of Lien and Ruthruff (2008) that task repetitions at lag 2 (i.e., ABA and BAB) are avoided.

In a second step, we focused on sequences of transitions. This analysis indicated that proportions of runs of lengths 1-10 depended on SOA and transition, whereas autocorrelations at lags 1-10 depended on SOA, transition and their interaction. In sum, the sequential analysis based on the transitions confirms that repetitions are the more frequent kind of transition, but any kind of transition shows a tendency to be followed by the other kind of transition so that a rather weak (local) alternation bias is present.

MODEL TESTING

In this section, we report the results of the model tests performed on the data that are reported in the previous section and that are representative of findings in other VTS studies. As already explained, the chain-retrieval model could work with chains of tasks and then it would predict task choices or it could work with chains of transitions and then it would predict transition selections. Therefore, we report two different tests of the chain-retrieval model. In the first test, we will use the information in task-run proportions to fit the model parameters and use these to predict autocorrelations. The second test is completely similar, but will be based on transition-run proportions to fit the model parameters. The results of the two tests will then be compared and discussed.

Each test follows the same sequence of analyses. First, we will present the results of fitting the chain-retrieval model to runs proportions obtained in the experiment. In order to provide an additional context for comparison, also the results of the statistical independence (Bernoulli) model and two dependency models are presented. One of these statistical dependency models is the perseveration model (Vandierendonck, 2000a). It assumes that with probability *a* the previous event is repeated and if no such repetition occurs, with probability *q* an event is sampled independently from the previous event:

$$Pr(x_i) = a + (1 - a)q \quad (3),$$

where $Pr(x_i)$ refers to the probability that a certain event (x) occurs at time i, *a* represents the probability that the previous event is repeated (perseverates) and *q* is the probability that the present event is sampled independently from the previous trial. The second dependency model is the alternation model (Vandierendonck, 2000a). This model is also based on equation (3): with probability *a* an alternation occurs (i.e., the previous event is not repeated) and if no alternation occurs, with a probability *q* an event is sampled independently from the previous event.

In a next step, the parameter estimations obtained in these fits of the four models (chain retrieval, Bernoulli, perseveration and alternation) will be used to predict the autocorrelations for sequences of tasks and sequences of transitions. After this phase of global model testing, more specific tests of the chain-retrieval model will be reported. To that end, each of the free parameters will in turn be clamped to a particular value and the other parameters will be estimated resulting in new fits and new predictions.

TASK-BASED TEST

Model fitting and parameter estimation

First we used the run proportions of the task-based data analysis to estimate the parameters of the task-chain retrieval model and the three comparison models, namely the statistical independence model, the perseveration model and the alternation model. Because the data of each individual subject are sufficient to fit the models, the runs data of each subject were used to estimate the free parameters of the best fitting model for that subject. The fits per subject could then be entered in statistical analyses comparing the merits of the models[5].

For the Bernoulli model, the single parameter was estimated separately for the magnitude task and the parity task data on the basis of the observed runs proportions length 1-10 and the degree of fit was calculated by comparing the predictions of the runs proportions on the basis of the estimated parameters with the observed values by means of formula (3). For the other models, a univariate search method (Brent, 1973) was used on the

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[5] This procedure has several advantages over the alternative procedure based on fitting the models on the between-subject average of runs. First, the processes described in the chain retrieval model and also those of the other dependency models are constrained by the skills and capacities of each subject. This variability is given the best chance by using individual data. Second, the between-subject average of the runs statistics does not adequately represent the processes that resulted in the generated random sequences. It is easy to imagine that the average runs of a subject generating a sequence with a repetition bias and another subject generating a sequence with an alternation bias will show either a very small bias or no bias at all.

basis of the same data. On each step of the iteration, the current parameter values were used to generate a sequence of 50,000 tasks. On the basis of this generated sequence, estimated runs for the magnitude task were calculated. Next the sequence was converted (0 was recoded to 1 and 1 to zero) to calculate the estimated runs for the parity task. The sum of squared differences between the estimated and the observed runs proportions of the 10 lengths in both tasks was then used as a goodness-of-fit measure,

$$f = \sum_{i=1}^{10} (o_i - e_i)^2 \quad (4),$$

where o_i is the observed proportion of runs at length i and e_i is the estimated proportion of runs at length i. The search procedure would then sample new parameter values and start a new step. This continues until a minimum is obtained. By performing the estimation jointly for the two tasks, the characteristic of random succession of the two tasks is captured in the parameter fit. The search procedure finds a local minimum in a very efficient way. In order to maximize the chance of finding the global minimum, the search procedure was applied ten times with random starting values. In the application for the task-chain model, this estimation procedure was repeated for each of the values 3-6 of *m*. Per subject, the value of the three parameters of the best fitting model was then selected.

Table 4 displays the fit and the estimated parameters of the four models. This table shows that the average fit over all subjects was quite good for each of the models, except for the alternation model. The fit of the task-chain retrieval was, however, much better than that of the other models: all *t*-tests comparing the fit of this model with the other models were significant. This significantly better fit to the task run proportions of the chain-retrieval model is interesting in that it suggests that the model better captures the relevant information in the data; however as the model has more free parameters, additional tests will be needed to show that the model is really better than the other ones.

Table 4. Comparison of the chain-retrieval model to statistical independence and dependence models in the task-based test. For each model variant the following results are shown: goodness-of-fit of the estimation (Fit), *t*-test of the difference with the chain-retrieval model, the estimated free parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this prediction with the prediction of the chain-retrieval model. The parameter *p* of the independence and dependence models is the probability of occurrence of the target task. In the parameter *r* column, for the perseveration and alternation models, the probability of respectively, a perseveration and an alternation, is shown. Further explanations in the text.

Models	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
Chain retrieval	0.005		3.95	0.60	0.31	0.012	
Statistical independence	0.013	2.64		0.53		0.027	4.28
Perseveration	0.008	2.58		0.49	0.16	0.031	8.88
Alternation	0.061	3.60		0.47	0.05	0.064	5.35

As an additional test of the goodness of fit, we tested whether the estimated parameter values captured differences between the subjects due to a short versus long SOA between the previous target and the present probe stimulus in the experiment. The estimated values of parameters *m* and *p* did not depend on the SOA, but the value of the *r* parameter did: with short SOA the parameter value was larger (M = 0.38) than with long SOA (M = 0.23), $F(1,78) = 14.30$, $p < .001$, $\eta_p^2 = .15$. This is consistent with the assumption that *r* represents the probability of intrusions which would be expected to occur more often at short SOA because of the larger repetition bias at short SOA (Arrington & Logan, 2004, 2005). Similarly, the estimated parameter of the Bernoulli model was larger (.55) with short than with long (.50) SOA, $F(1,78) = 7.83$, $p < .01$, $\eta_p^2 = .09$, which is also a way to capture the more frequent repetitions under short SOA. In the perseveration model, only the perseveration parameter was sensitive to SOA, with a larger perseveration tendency at short (.22) than at long (.10) SOA, $F(1,78) = 8.11$, $p < .01$, $\eta_p^2 = .09$. This is again consistent with the findings of a larger repetition tendency at short SOA. In the alternation model, the alternation parameter was not, but the general probability was sensitive to SOA with a smaller probability at short (.45) than at long (.48) SOA, $F(1,78) = 5.67$, $p < .05$, $\eta_p^2 = .07$. As the alternation parameter can only capture task alternations, the only way for this model to cope with the difference due to SOA is by having a larger general probability. This also shows that the alternation model is not really suited to account for these data.

Model predictions

The estimated parameters of these four models were used to predict the autocorrelation statistic for both the task data and the transition data. In order to keep task and transitions statistics equivalent in terms of number of events, lags 1-10 were used for the task data and lags 1-9 for the transition data. In order to calculate the predictions of the models, also a sequence of 50,000 events was generated and the predicted statistic was calculated from this sequence. In order to obtain transition statistics, the generated sequence was converted to transitions, once with focus on repetitions and once with focus on switches. The correspondence of the predictions and the data is shown in Figure 3 for the predictions of the task autocorrelations (top) and the transition autocorrelations (bottom). The outcomes of the statistical tests of this correspondence are displayed in Table 4 in the column labeled ‘Prediction’. Figure 3 illustrates that the task-chain retrieval model yielded the best correspondence between predictions and data, and this was confirmed by the significant difference with each of the other models (Table 4). When applied to data that are more sensitive to deviations from statistical independence than the runs statistic, it seems that the chain retrieval model significantly better accounts for these deviations than the other dependence models.

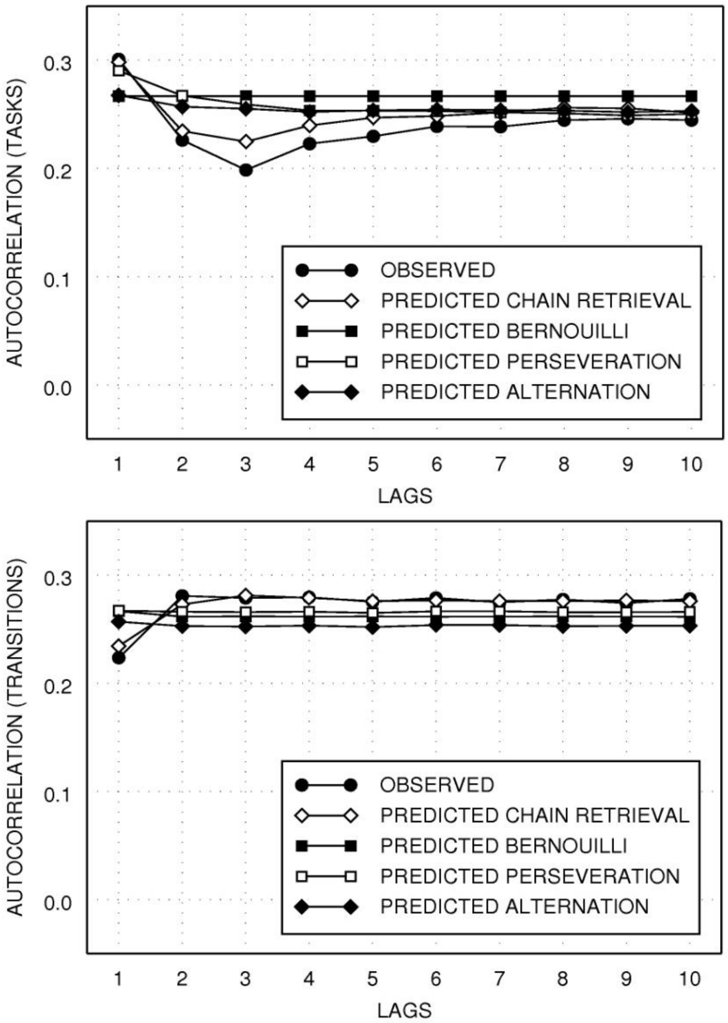

Figure 3. Observed and predicted proportions of autocorrelations lag 1-10 in the task-based tests. Top Panel: Besides the observed task choice autocorrelations, the predictions of the chain-retrieval, the Bernoulli, the perseveration and the alternation models are shown. The predictions of the chain-retrieval model seem to correspond best with the data. Bottom Panel: Observed transition autocorrelations and predictions by the same models. The figure shows lags 1-10, although for the predictions only 9 lags were used. The predictions of the chain-retrieval model seem to correspond best with the data.

Model validation

As the model has three free parameters, it is also important to know whether each of the parameters is indispensable. To that end, each of the parameters in turn was clamped and with one parameter fixed, new estimations of the other two parameters were obtained. Table 5 and Figure 4 show that in the absence of bottom-up triggering of repetitions (r = 0), in the absence of a preferential retrieval of chains with repetitions (p = 0.5), and with a minimal working memory capacity (m = 3), the fit and the predictions were dramatically worse. This shows that all these parameters and the underlying processes are needed to account for the data.

Table 5. Comparison of the fixed-parameter versions and the free parameter version of the chain-retrieval model in the task-based test. For each model variant the following results are shown: goodness-of fit of the estimation (Fit), *t*-test of the difference with the free-parameter chain-retrieval model, the estimated parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this prediction with the prediction of the full-parameter chain-retrieval model. Further explanations in the text.

Models	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
Chain retrieval full version	0.005		3.95	0.60	0.31	0.012	
Chain retrieval m = 3	0.006	5.29	**3.00**	0.55	0.38	0.015	5.02
Chain retrieval p = 0.5	0.007	6.18	3.95	**0.50**	0.36	0.014	3.44
Chain retrieval r = 0.0	0.032	2.23	5.35	0.77	**0.00**	0.031	4.21

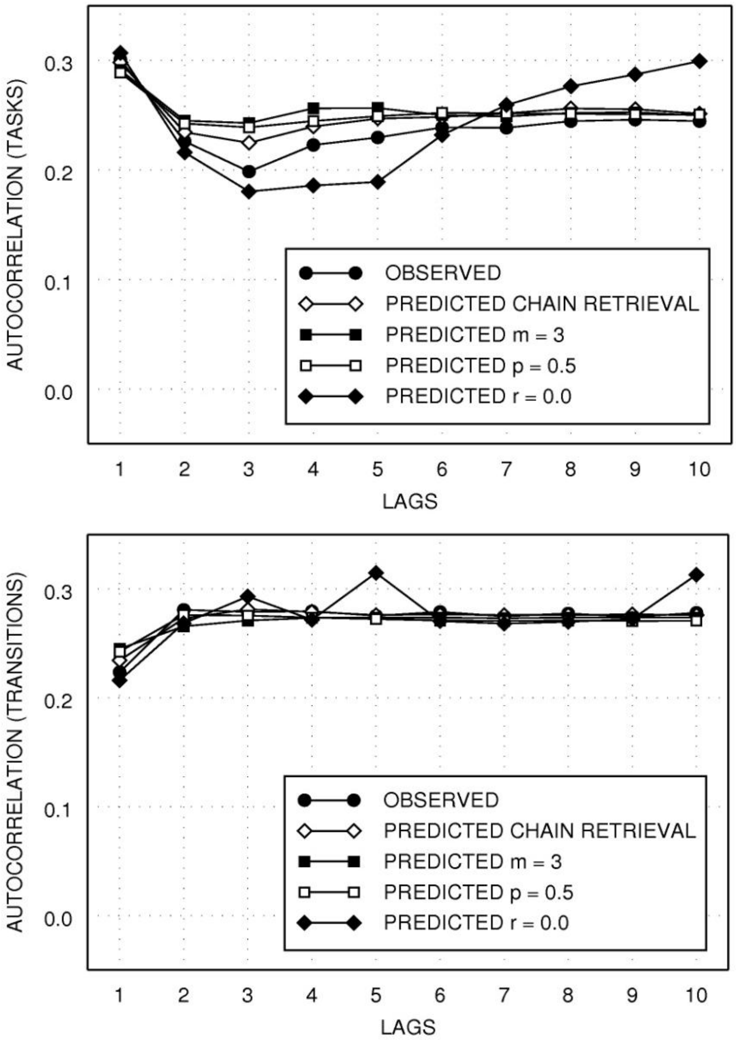

Figure 4. Observed and predicted proportions of autocorrelations lag 1-10 in the task-based test. Top Panel: The predictions of the task choice autocorrelations by the full chain-retrieval model (3 parameters) and of the three versions with the value of one parameter clamped to a neutral value. The predictions of the complete chain-retrieval model correspond best with the data. Bottom Panel: Same for the transition autocorrelations lag 1-10. The figure shows lags 1-10, although for the predictions only 9 lags were used. The predictions of the chain-retrieval model seem to correspond best with the data.

Discussion

The chain-retrieval model seems quite promising when fitted to sequences of tasks. Compared to the statistical independence model and existing statistical dependence models, both the parameter fit to the runs proportions and the predictions of the autocorrelation statistic yielded a better correspondence to the data than each of these other models. In a final test designed to investigate whether the processes underlying the three free parameters are all involved in achieving this good correspondence, each of the parameters in turn was clamped to a neutral value so as to exclude or to minimize the role of the underlying process. These analyses indicated that all three parameters of the model and the underlying processes are important in achieving the good correspondence with the data. Other assumptions for the underlying processes of the model were also investigated; these are reported in Appendix A. The appendix shows that changing the present assumptions does not seem to improve the chain-retrieval model fitted to task sequences.

TRANSITION-BASED TEST

Model fitting and parameter estimation

The same procedure was followed to estimate the best fitting parameters of the chain-retrieval model on the basis of the proportions of transition runs and it was compared with the fits of the three comparison models on the same data. In order to use an equivalent amount of data, runs lengths 1-9 were used for parameter estimation. The procedure used was otherwise the same as the one used in the task-based test. Table 6 displays the fit and the free parameters obtained. Fits to the transition run proportions were very good for all four models, and in fact the fit of the chain-retrieval model was only significantly better than the fit of the perseveration model and was not reliably different from the fit of the other two models. These results indicate that all four models were efficient in capturing the information available in the sequence of transitions.

Table 6. Comparison of the chain-retrieval model to statistical independence and dependence models in the transition-based test. For each model variant, the following results are shown: goodness-of fit of the estimation (Fit), *t*-test of the difference with the chain-retrieval model, estimated free parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this prediction with the prediction of the chain-retrieval model. The parameter *p* of the independence and dependence models is the probability of occurrence of the target task. In the parameter *r* column, for the perseveration and alternation models, the probability of respectively, a perseveration and an alternation, is shown. Further explanations in the text.

Models	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
Chain retrieval full version	0.008		4.29	0.65	0.26	0.009	
Statistical independence	0.013	0.79		0.52		0.026	5.00
Perseveration	0.008	0.10		0.55	0.02	0.031	9.43
Alternation	0.061	3.20		0.72	0.31	0.064	5.57

We also analyzed the values of the parameters of the four models in relation to the design factor SOA. Parameters *m* and *p* of the transition-chain model did not depend on the SOA between the previous target and the present probe stimulus, but the value of the *r* parameter did: with short SOA, the *r* parameter value was larger ($M = 0.30$) than with long SOA ($M = 0.22$), $F(1,78) = 4.34$, $p < .05$, $\eta_p^2 = .05$. This again shows that the larger repetition tendency at short SOA can be accounted for by the presence of more bottom-up triggered repetitions at short SOA. Similarly, the estimated parameter of the Bernoulli model was larger (.55) with short than with long (.50) SOA, $F(1,78) = 7.79$, $p < .01$, $\eta_p^2 = .09$; this captured the stronger repetition bias at short SOA. In the perseveration model, only the general probability parameter was sensitive to SOA, with a larger value at short (.58) than at long (.51) SOA, $F(1,78) = 7.57$, $p < .01$, $\eta_p^2 = .09$. That the general probability changes with SOA, is also indicative of a rather poor fit of this model, because with a good fit, the perseveration parameter should capture this information. In the alternation model, neither of the parameters was sensitive to SOA. This also suggests that this model does not capture important aspects of the data.

Model predictions

The estimated parameters were next used to predict the transition autocorrelations (lags 1-9) and the task autocorrelations (lags 1-10). Important differences in the correspondence of predictions and data of the four models were observed. Table 6 and Figure 5 both show that the correspondence between data and predictions was best for the chain-retrieval model. This model's predictions were significantly better than those of each of the three comparison models, which all demonstrated rather bad correspondence to the data.

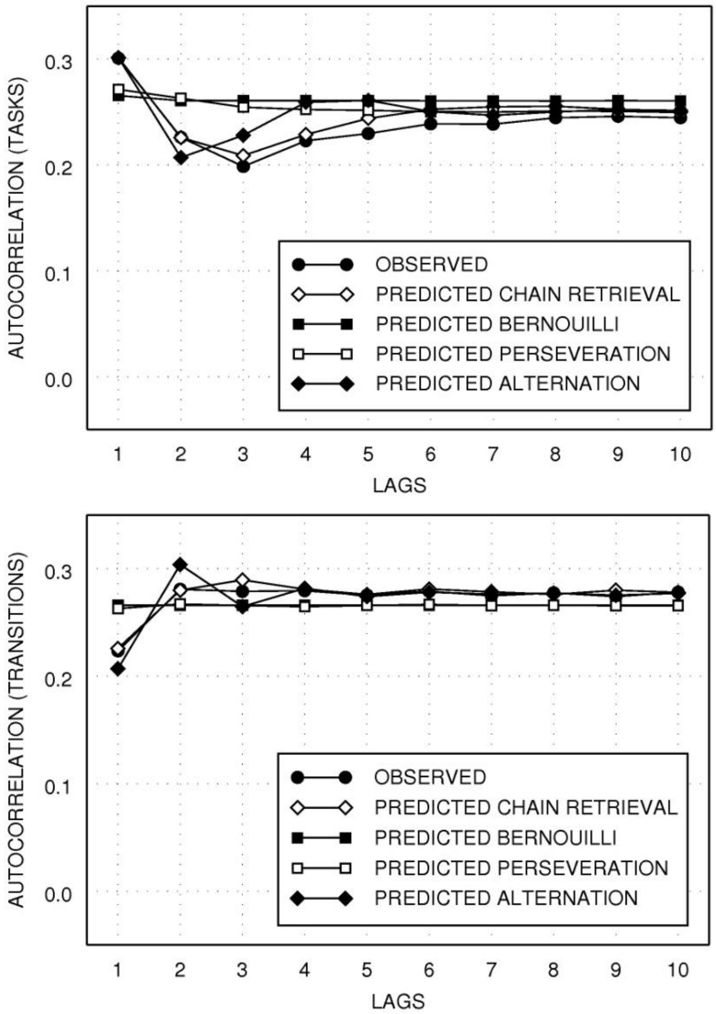

Figure 5. Observed and predicted proportions of autocorrelations lag 1-10 in the transition-based test. Top Panel: Besides the observed task autocorrelations, the predictions of the chain-retrieval, the Bernoulli, the perseveration and the alternation models are shown. The predictions of the chain-retrieval model seem to correspond best with the data. Bottom Panel: Observed transition autocorrelations and predictions by the same models. The figure shows lags 1-10, although for the predictions only 9 lags were used. The predictions of the chain-retrieval model seem to correspond best with the data.

Model validation

In order to test the role of the processes underlying the three free parameters, each of the parameters was in turn clamped to a neutral value. With this value fixed, a new fit was obtained with the remaining parameters. On the basis of these fits, predictions for the autocorrelation statistic were calculated. Table 7 shows the comparisons of these three versions of the model with the full-parameter model. Clearly, the fits and the predictions of these restricted models are all worse than those of the full-parameter model. Figure 6 shows that these predictions deviate strongly from the autocorrelation data and from the predictions of the full-parameter model. These findings show that the processes underlying the three free parameters all contribute to the model's predictions.

Table 7. Comparison of the fixed-parameter versions of the chain-retrieval model to the full-parameter version in the transition-based test. For each model variant the following results are shown: goodness-of fit of the estimation (Fit), *t*-test of the difference with the transition-chain model, estimated free parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this prediction with the prediction of the chain-retrieval model. Further explanations in the text.

Models	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
Chain retrieval full version	0.008		4.29	0.65	0.26	0.009	
Chain-retrieval m = 3	0.014	4.68	**3.00**	0.62	0.37	0.014	5.78
Chain-retrieval p = 0.5	0.021	5.50	4.03	**0.50**	0.37	0.013	5.99
Chain-retrieval r = 0.0	0.061	2.23	5.31	0.76	**0.00**	0.025	4.32

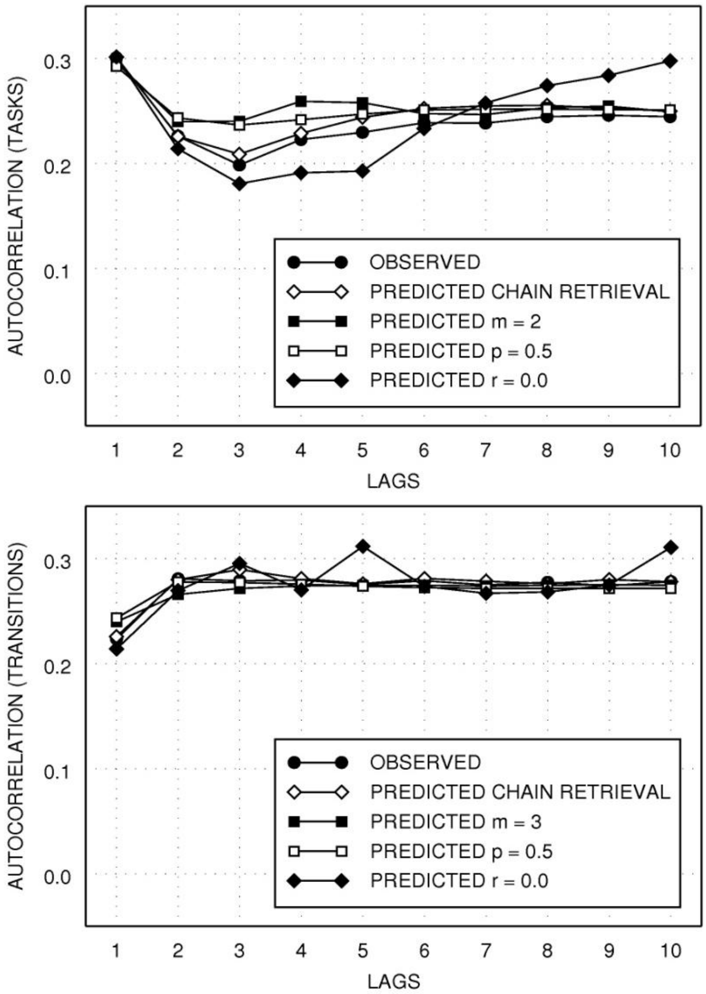

Figure 6. Observed and predicted proportions of autocorrelations lag 1-10 in the transition-based test. Top Panel: The predictions of the task autocorrelations by the full chain-retrieval model (3 parameters) and of the three versions with the value of one parameter clamped to a neutral value. The predictions of the complete chain-retrieval model correspond best with the data. Bottom Panel: Same for the transition autocorrelations lag 1-10. The figure shows lags 1-10, although for the predictions only 9 lags were used. The predictions of the chain-retrieval model seem to correspond best with the data.

Discussion

The transition-based tests of the chain-retrieval model show that although the fits of the model on the transition-run proportions were not reliably better than those obtained with the independence and the perseveration model, the predictions of the chain-retrieval model were much better than the predictions of these other models. Besides, the full-parameter model also yielded better fits and better predictions than the restricted models with one of the parameters clamped to a neutral value. This suggests that the processes underlying these parameters all contribute to the good fit of the model. An analysis of changes in other assumptions of the chain-retrieval model when fitted to transition data is presented in Appendix B. None of these changes constitutes an improvement of the model.

Comparison and discussion

It was already clear from the empirical data that the task and transition sequences contain different information and this is reflected in the fits of the chain-retrieval model to these two aspects of the data. A more direct test of this tentative conclusion was attempted by comparing the fits and the predictions of the model in the two data-sets. In a first analysis, the average goodness-of-fit of the chain-retrieval model was not significantly different between the task-based and transition-based fits ($F < 1$). The second analysis of variance based on a 2 (Test: task-based vs. transition-based) × 2 (Statistic: task vs. transition autocorrelation) design was used to compare the goodness-of-prediction (the degree of correspondence between observations and predictions of autocorrelations as defined in equation 4). Overall, the goodness-of-prediction value was smaller (better) in the transition-based than in the task-based analysis, $F(1,79) = 31.69$, $p < .001$, $\eta_p^2 = .29$. Although no overall difference in goodness-of-prediction for the task and the transition autocorrelations was observed, this factor interacted with the factor test, $F(1,79) = 13.53$, $p < .001$, $\eta_p^2 = .15$. This interaction was due to a poorer prediction of the task autocorrelations in the task-based test (M =

.009) than in the transition-based test (*M* = .006), while no such clear difference was present for the transition autocorrelations (.007 vs. .005).

These analyses demonstrate that the goodness-of-prediction was reliably different between the task-based and the transition-based application of the chain-retrieval model, even though the goodness-of-fit did not differ across the two applications and related data aspects were used to fit the model. This suggests that the transition data contain more useful information than the task data.

Given that there is variability in the goodness-of-fit and goodness-of-predictions in the subject sample, it may be considered that some of the subjects rely more on the sequence of tasks, while the other subjects rely more on the sequence of transitions. In order to test this, the subjects were partitioned according to their goodness-of-fit in the two tests. This resulted in a group of 34 with a better goodness-of-fit value in the task-based test than in the transition-based test, and a group of 45 that obtained a better goodness-of-fit in the transition-based test than in the task-based test. One subject was excluded because both fit values were equal. While the average goodness-of-fit obtained in the transition-based test tended to be better (*M* = .0009) than the one obtained in the task-based test (*M* = .0014), the difference was not reliable ($p > .25$). For each subject in the two groups, the goodness-of-prediction values obtained with their best fit were subjected to an analysis of variance based on a 2 (Test: task-based vs. transition-based) × 2 (task vs. transition autocorrelations) factorial design with repeated measures on the last factor. This analysis revealed a main effect of group with a better goodness-of-prediction in the transition-based group (*M* = .004) than in the task-based group (*M* = .009), $F(1,78) = 5.05$, $p < .05$, $\eta_p^2 = .06$. This was the only significant effect. The prediction of the transition autocorrelation seemed to better in the transition-based group (.003) than in the task-based group (.009), $F(1,78) = 4.65$, $p < .05$, $\eta_p^2 = .06$. Also the prediction of the task autocorrelation was better in the transition-based group (.005) than in the task-based group (.009), $F(1,78) = 4.83$, $p < .05$, $\eta_p^2 = .06$.

These analyses show that even when for each subject in the sample, the best fit of the two was selected, the parameter values obtained in the transition-based test still yielded better predictions than the parameter values obtained in the task-based test. This advantage was present as well in the transition autocorrelations as in the task autocorrelations. These findings suggest that the information available in the sequence of transitions is more useful than the information contained in the sequence of tasks. Interestingly, this result is obtained on the basis of a model which is neutral with respect to whether task information or transition information is used to feed the task selection process. This indicates that transition information is used by a majority of the subjects, probably in the chain representations in LTM.

GENERAL DISCUSSION

OVERVIEW OF THE FINDINGS

The objective of the present study was to develop and test a model of task choice in VTS. Taking into account findings from earlier work on random generation, we hypothesized that subjects acquire chains containing task information. In task selection, such chains are retrieved from LTM to guide the trial-by-trial choice of tasks. We assumed that working memory capacity constrains the length of the chains retrieved, that chains with more repetitions tend to be more likely to be retrieved, and that bottom-up triggered repetitions intrude into the sequence of task selections made. This view was specified in a model with three free parameters corresponding to these assumed processes. This model's performance was compared with that of a statistical independence model (Bernoulli) and with performance of two statistical dependence models, one with a repetition bias (perseveration model) and one with an alternation bias (alternation model).

For the purpose of a comparative test of these models, task choice sequences were collected. These data were analyzed from two perspectives, namely as a sequence of tasks and as a sequence of transitions between tasks. The task-based analysis of these data confirmed the task repetition bias in task selection (e.g., Arrington & Logan, 2004). However, the autocorrelation statistic showed that this bias was only present at lag 1, which is consistent with the avoidance of lag-2-repetitions in VTS (Lien & Ruthruff, 2008). In other words, when subjects executed task A, there is a tendency to immediately repeat task A (lag-1 repetition/autocorrelation), and next to switch back and forth between the two tasks (in the lag 2-5 window). At longer lags (longer than 5), there is no strong evidence for a statistical dependency.

The transition-based analysis of the choice data showed a dominance in the proportion of repetitions, but between the two types of transitions an alternation bias was observed. This means that subjects seem to be reluctant to keep using the same transition twice in a row.

Because of these two ways of analyzing the data, the chain-retrieval model and the models in the comparative analysis were tested twice, once by fitting the model parameters to the task data and once by fitting the model parameters to the transition data. In both tests, for most models in the comparison an appropriate fit to the runs proportions was obtained. However, only the chain-retrieval model produced an adequate correspondence between predicted and observed autocorrelations. The poorer correspondence of the independence model with the data indicates that the task and/or transitions selected by subjects in VTS are not statistically independent. The rather poor correspondence of the statistical dependence models indicates that the statistical dependence in the subjects' choices is quite specific and this specificity seems to be adequately accounted for by the chain-retrieval model.

Comparing the two tests, it was noteworthy that although the chain-retrieval model obtained similar goodness-of-fit in the two situations, the predictions in the transition-based test were significantly better than those in the task-based test. This suggests that the transition data contain more useful information that is picked up in parameter estimation. Taking this one step further, this finding is consistent with the hypothesis that subjects in a VTS experiment are storing and using the transition information and this could explain why the transition-based model fit is able to better grasp the statistical properties of the sequence of generated tasks and transitions. The present data do not allow a decisive conclusion in this respect, and further tests of this hypothesis that transition information rather than task information is used in VTS are indispensable to settle this issue.

The three free parameters of the model correspond to a number of hypothesized processes. In order to test whether each of these processes contributes to the model's performance, each of the parameters in turn was clamped to a neutral value while the other two parameters were freely estimated. These analyses confirmed that all three hypothesized processes are critical to account for the model's performance. More specifically, there seems to be individual variation in the length of the chains retrieved from LTM and maintained in working memory. There also seems to be a preference for retrieving chains with more repetitions and bottom-up intrusions seem to occur at a certain rate. In fact, it can be imagined that not all situations involving a bottom-up priming lead to an intrusion because endogenous control processes probably intervene to block some of these potential intrusions. We did not include a fourth parameter to model this endogenous process, though, because its effects would be completely absorbed in the rate at which intrusions do occur. In practice, this means that the parameter r can be interpreted as the result of the occurrence of bottom-up events and the blocking of part of these events by control processes.

While the present study supports the chain-retrieval model, the evidence considered here also has some limitations. For one thing, the model test was based on data of only one experiment that used the double-registration procedure of VTS. It may be objected, therefore, that the validity of the model is limited to situations where the task must be explicitly indicated before the task stimulus appeared. A similar objection may evidently be raised against the empirical part of the present study. Until now, many VTS studies used the single-registration methodology in which each task is assigned to a particular hand so that the task selection is apparent from the hand used to respond to the target. It is possible that the present observations are specific to the double-registration procedure. In order to counter this criticism, we analyzed the data of a single-registration VTS experiment (Liefooghe et al., 2009). Although the experiment was based on a smaller number of subjects (18) and each subject performed only 4 blocks of 64 trials, we observed the same pattern of results regarding runs proportions and autocorrelations. Taking this into account, it seems that the findings reported here can be considered as representative for VTS in general. We also applied the task-chain model to these data and even though the data were noisier, we replicated the findings that the model yielded excellent fits and that the predictions obtained with a transition-based parameter estimation were better than those obtained with a task-based parameter estimation. This application of the model to data from a single-registration experiment shows that the findings reported in the present article are not specific for the double-registration procedure.

THEORETICAL IMPLICATIONS AND AVENUES FOR FURTHER RESEARCH

In this section, we discuss the theoretical basis and implications of the assumptions we made in developing the chain-retrieval model. This discussion considers the assumptions related to the three free parameters.

The three parameters of the model were introduced to grasp particular constraints of the task selection process in VTS. Parameter m was introduced to specify the amount of working memory available for this aspect of the task. Considering that the retrieved chain has to be kept in working memory until all events in the sequence have been used for task execution, the allowed length of the sequence is determined by this parameter. The usage of this parameter is consistent with a number of findings that have been reported in studies in which random generation was used to tax executive or cognitive control. In particular, Baddeley et al. (1998), for example, found that the deviation of randomness in generated key presses increased when an irrelevant memory load was larger, which shows that maintaining a memory load may interfere with cognitive control processes needed for the generation task. Several studies have also reported poorer recall on a memory task when an unrelated random generation task was performed concurrently (e.g., Fisk & Sharp, 2003; Macizo, Bajo, & Soriano, 2006; Towse & Cheshire, 2007; Vandierendonck, 2000a, 2000b; Vandierendonck, De Vooght, & Van der Goten, 1998a, 1998b; Vandierendonck, Kemps, Fastame, & Szmalec, 2004), suggesting that random generation interferes with maintenance of unrelated memory contents. Based on these findings, the expectation could be formulated that performing VTS under a memory load should result in the usage of shorter chains. However, the impact of a memory load depends on working memory capacity. Persons with a larger working memory capacity are more able to maintain a load while performing another cognitive demanding task (e.g., Engle, Kane, & Tuholski, 1999). Therefore, the expectation that shorter chains would be used in VTS under a memory load would probably mainly affect persons with a low working memory capacity.

Related to the effect of a memory load, it must be considered that such a load increases the task-repetition bias (Demanet et al., in press). It is quite likely that a memory load sets the stage for more bottom-up intrusions (see e.g., Lavie, Hirst, de Fockert, & Viding, 2004); consequently, the r parameter is expected to increase when load increases, also because the control processes that block upcoming intrusions are expected to be less efficient when there is a working memory load. If it is the case that under load, task switching would become more difficult, this would also imply that a larger p-value would be expected under load than without load. This could also imply that low working memory subjects would also be more vulnerable to the effects of load and develop a stronger bias towards repetitions. Taken together, in an individual differences approach, subjects with larger working memory capacity should be observed to generate longer sequences of events, and they would be expected to be less vulnerable to bottom-up intrusions. In terms of the modeling, high working memory subjects should show a larger value for *m* and a smaller value for *r* and *p* than low working memory subjects.

A second parameter, *p*, biases the selection of sequences in such a way that sequences are more likely to be retrieved when they contain more repetitions compared to when they contain more alternations. The inclusion of the *p* parameter in the modeling shows that the probability of retrieving particular chains depends on the ease of execution. The values obtained for *p* were clearly above 0.5 (even higher than 0.6) so that it seems that subjects were sensitive to the difficulty of the task transitions. If the model would be applied to random generation tasks, this parameter would be useless because the ease of execution is not relevant. In other words, if in a VTS design subjects were not required to execute the chosen tasks, the value of *p* would become irrelevant, and this would result in task selection that is not sensitive to the difficulty of switching. In a similar vein, if subjects would not be sensitive to the ease of task execution, the value of the parameter would probably have been close to 0.5 or it could even have been smaller than 0.5 which would then reflect a bias towards sequences with switches (e.g., Rapoport & Budescu, 1997).

The good correspondence of the model's predictions and the data is consistent with the idea that there is a bias towards a selection of sequences with more repetitions. How can this be explained? One obvious possible explanation relates to the assumption we adopted to motivate the inclusion of the *p* parameter, namely that subjects develop such a bias during task execution on the basis of the experience that repetitions are easier to execute than switches. Whether subjects indeed develop a bias towards a larger *p* value, is one of the avenues for further research that follows from the present modeling attempt. Making switching easier or more difficult to execute should affect the value of this parameter. This is in line with Botvinick's integrative account of the functioning of the anterior cingulate cortex (Botvinick, in press).

Interestingly, the *p* parameter may be considered to yield a measure of the degree to which repetitions are favored in the selection of tasks. This would possibly be a better measure than one often used now, namely the proportion of task repetitions in the sequence, because the latter measure not only counts generated repetitions but also bottom-up triggered repetitions. A drawback of this proposal is that in order to know the value of *p* the model's parameters must be estimated, which is time consuming because it involves statistical analysis of the task sequence, and parameter estimation.

The third parameter, *r*, specifies the probability that a repetition intrudes in the generated sequence. The estimated value of *r* shows that these events play an important role as its value suggests that more than 1/4 of the trials were affected by it. This parameter was included to account for previous findings regarding bottom-up effects in VTS. The parameter value also suggests that these kinds of events are happening quite often. This confirms the difficulty of remaining in control of task selections while trying to avoid to be distracted by exogenous events (Mayr & Bell, 2006). Another interpretation of this parameter is that it may reflect execution errors on the part of the subjects. Erroneously executing a repetition instead of a switch would have the same effect. Given that error rates in task-switching research are usually around 5%, errors cannot completely account for the value of *r*. The interpretation that *r* represents bottom-up intrusions that could not be blocked by top-down control mechanisms is also supported by the observation that the size of *r* depended on the SOA between the previous stimulus and the present task probe. The value of *r* was namely larger with a short SOA. This is exactly what would be expected if this parameter is related to intrusions. On the same count, no such effect is expected for the other parameters and this was also confirmed. Further tests of the model could include other well chosen design variations, such as the number of target repetitions (Mayr & Bell, 2006) or invoked response repetitions (Demanet et al., under revision). Data based on such procedural variations should lead to larger values for *r* in conditions that result in more repetitions.

It is interesting to note that like the parameter *p*, the *r* parameter in the model is tightly related to the fact that in VTS task executions are required. Two out of three model parameters are directly related to this particular feature of VTS, which is not present in typical random generation tasks. This should make it clear that although random generation is common to both task settings, the requirement to randomly select tasks in VTS is done in the service of another goal and is not a goal on its own as in random generation tasks.

The joint effects of the bias towards selecting chains with repetitions (*p* parameter) and the intrusion of repetitions (*r* parameter) in the chain-retrieval model, may raise the suspicion that the repetition bias as presently modeled is stronger than the repetition bias as typically observed in VTS. One should bear in mind, though, that the sequences of tasks that comply with the criterion of equal task frequency are in general biased towards alternation. Inspection of Table 1 makes this abundantly clear. Sequences of 4 tasks (3 transitions) contain on average 3 repetitions and 6 switches. In combination with a 25 % chance of repetition intrusions this leads to a small repetition bias. Furthermore, the parameter tests confirmed that both parameters are critical in obtaining a good fit of the models.

VOLUNTARY TASK CHOICE

While the present study was completely framed within the VTS procedure, the modeling reported here, does have implications that go far beyond VTS. First, the model presented here, was designed to provide an explanation of task choice in VTS, but it can also account for the different pattern of findings in randomization behavior in a range of task settings. The model is, for example, also applicable to binary randomization tasks (e.g., coin tossing). Such an application should be successful with parameters *p* and *r* fixed. In fact, with only retrieval of balanced sequences of events, the model could also be considered as a variant of the Rapoport and Budescu

(1997) model: on the one hand, the balanced sequences are similar to plausible random sequences in their model; on the other hand, instead of building the sequence on-line as in their model, the sequence is retrieved from LTM.

Second, the chain-retrieval model implements a cluster of hypotheses about the cognitive processes involved in task selection. The fact that in the VTS procedure, subjects are requested to generate tasks in a random order may be seen as an attempt to curtail voluntary task choice. Indeed, when no constraints are imposed on the tasks chosen, the frequency of switches is very low (Kessler, Shencar, & Meiran, 2009; Liefooghe et al., in press). In order to collect useful data in a task-switching paradigm, instructions that increase the number of task switches are necessary. Usage of randomization instructions, no doubt, helps in achieving this goal. An important question is whether this occurs at the expense of voluntary task choice. Research on random generation has convincingly shown that trying to be random requires a continuous attempt to block or interrupt automatic responding (Baddeley, 1996; Baddeley et al., 1998; Towse & Cheshire, 2007). It can be said that each time an automatic response is successfully blocked, this response is 'voluntary'. Similar observations have been reported in VTS research. For example, Mayr and Bell (2006) report that individuals who are slower in repetition trials but not in switch trials are less vulnerable to bottom-up triggered task repetitions. These individuals seem to have more top-down control and have more voluntary task choices than individuals who do not show such selective slowing. In the same vein, ERP-research in VTS indicates that there is a strong tendency to repeat the task even before the stimulus is presented, but that on a proportion of the trials, this tendency is overruled to execute a switch (Vandamme et al., in press). If there is a controlled slowing in handling this preparedness to repeat, it seems evident that suppressing the repetition and executing a switch instead becomes more likely. Working memory loads are often used to interfere with top-down control (see Lavie, 2005, for a review). Usage of this method in VTS has shown that under load, top-down control becomes less efficient and the probability that bottom-up triggered events intrude into the sequence of selected tasks becomes larger (Demanet et al., in press), which again suggests that voluntary task selection also involves blocking of ‘unwilled’ choices. In terms of the task-chain model, this means that the more choices are voluntary, the lower the value of *r* should be. As the average value was lower at long than at short SOA, it seems that at long SOA more voluntary task choices were made. Although the upper value of how frequently bottom-up intrusions occur is not known, the changes in the value of parameter *r* could be used to estimate variations in the extent to which voluntary task choice does occur.

Notwithstanding the stress on processes involved in ‘task choice’, the present study also indicates that we cannot be sure that it is really task choice that matters. The chain-retrieval model as developed here with retrieval of chains of tasks from LTM is parametrically not distinguishable from a model with the same assumptions but based on the storage of chains of transitions in LTM. The reason that this distinction is not possible is because the chains stored in the two versions of the model are completely equivalent. Nevertheless, we observed that when the parameters were fitted on the basis of transition sequences, the model yielded better corresponding predictions than when the parameters were fitted on the basis of task sequences. This indicates that people seem to prefer transitions over tasks, which is consistent with ERP-findings (Vandamme et al., in press). Yet, the usage of transitions may be restricted because transitions are useless if the choice would be among more than two tasks. As the mechanism behind task-chain retrieval remains unclear, further research about which information (tasks or transitions or both) is stored in LTM, and how this information is coded would be useful.

The idea of retrieving stored chains of tasks is quite similar to retrieving a plan of actions. When people make a plan, in order to achieve the goal, appropriate subgoals are retrieved and chained into a sequence of steps. These chains are stored in LTM and can be retrieved for later usage. The retrieved chains guide task execution which subsequently results in achieving the goal. In other words, the chain-retrieval model can be considered as a special case of more general goal-directed processing and of planning in particular. It is no coincidence that there are some similarities between the present modeling and the task-span procedure introduced by Logan (2004, 2006).

CONCLUSION

The present study showed that the repetition bias in VTS is due to a locally-based statistical dependency in the sequence of selected tasks or transitions. The model based on a chain retrieval accounts very well for these data and suggests (a) that short sequences of tasks (or maybe transitions) are retrieved from memory, (b) that these sequences of tasks are maintained in working memory to guide task selection, (c) that the length of these sequences is constrained by working memory capacity, and (d) by the probability that the sequences contain repetitions linked to ease of execution, and finally (e) that bottom-up intrusions of repetitions play an important part in the repetition bias. This model has a number of implications that can be tested in future research. The memory processes postulated in the model propose a hypothesis on how randomization in general and more particularly how task selection in VTS may occur. The assumption that task selection is based on chains of events retrieved from memory provides a possible answer regarding the cognitive control of task selection, namely that in VTS, not single tasks but chains of tasks or possibly even action plans are selected. Finally and not least important, the modeling also indicates that the adjective 'voluntary' in voluntary task switching may refer to the process of selecting tasks but also to the process of blocking intrusions.

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APPENDIX A

ADDITIONAL TASK-BASED TESTS OF CHAIN-RETRIEVAL MODEL

Using the same formal basis defined by the three parameters of the chain-retrieval model, other assumptions can be made to implement model variations. Instead of merging the end of the previous chain with the start of the following chain, the task-chain retrieval model could use concatenation of chains. With respect to the bottom-up intrusions, instead of assuming that the activated chain can be kept on hold and is continued afterwards (the present model), the intrusion can replace one of the events in the activated chain or the activated chain could be aborted when the intrusion occurs. In order to account for these variations, each of them has been tested as a variation of the model as outlined in the main text. The results of the tests of these model variations are presented in Table A1, which compares the goodness-of-fit and the correspondence of the predictions of the task-chain retrieval model with other possible assumptions that could have been made. The table also gives the values of *t*-statistics for the contrast of the model with these other variants.

The table shows that the model yields a better fit to the observed runs proportions than all the other variants tested, except for the variant where the bottom-up intrusion replaces the task selected from memory instead of postponing the selected task to the next trial. However, the predictions of that variant were significantly poorer than the predictions of the reference model. In fact, the chain-retrieval model's predictions were significantly better than those of the variants.

Table A1. Comparison of model variants of the chain-retrieval model. The table compares the basic version of the model to variations of the model in which one assumption was changed. For each model variant the following results are shown: a specification of the assumptions made, goodness-of fit of the estimation (Fit), *t*-test of the difference with the target model, the estimated free parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this measure and the target model. Explanations in the text.

Models[a]	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
merge-intrude (basis)	.005		3.95	.60	.31	.012	
concatenate-intrude	.006	5.09	4.09	.58	.25	.013	2.62
merge-replace	.005	-2.64	4.41	.66	.28	.013	1.81
merge-restart	.006	2.79	4.20	.63	.26	.012	1.13

a The models differed from each other with respect to whether on retrieval the chains are simply concatenated or merged (combining the first element of the new chain with the last element of the previous chain), and whether intrusions merely intrude (and keep the chain intact), replace the current element of the chain or result in losing the chain from memory so that a restart is needed.

APPENDIX B

ADDITIONAL TRANSITION-BASED TESTS OF CHAIN-RETRIEVAL MODEL

In a similar way the assumptions of the chain-retrieval model were tested on the transition-based model fitting. The same alternatives were tested. The results of the tests of these variations are presented in Table B1, which compares the goodness-of-fit and the correspondence of the predictions of the chain-retrieval model with other possible assumptions that could have been made. The table also gives the values of *t*-statistics for the contrast of the model with these other variants.

As for the task-based tests, the table shows that the transition-based tests of the chain-retrieval model yields a better fit to the observed transition runs proportions than all the other variants tested. The predictions of all these variants were significantly poorer than the predictions of the reference model. In fact, the chain-retrieval model's predictions were significantly better than those of the variants.

Table B1. Comparison of model variants of the chain-retrieval model. The table compares the basic version of the model to variations of the model in which one assumption was changed. For each model variant the following results are shown: a specification of the assumptions made, goodness-of fit of the estimation (Fit), *t*-test of the difference with the target model, the estimated free parameters, goodness-of-prediction of the autocorrelation statistics (Prediction), and *t*-test of the difference of this measure and the target model. Explanations in the text.

Models[a]	Fit	t(78)	*m*	*p*	*r*	*Prediction*	*t(78)*
merge-intrude	.008		4.29	.65	.26	.009	
concatenate-intrude	.011	2.64	4.45	.65	.22	.011	2.05
merge-replace	.046	12.93	4.68	.52	.56	.035	10.74
merge-restart	.062	3.17	3.80	.17	.38	.029	7.33

a The models differed from each other with respect to whether on retrieval the chains are simply concatenated or merged (combining the first element of the new chain with the last element of the previous chain), and whether intrusions merely intrude (and keep the chain intact), replace the current element of the chain or result in losing the chain from memory so that a restart is needed.

Chapter 6
General discussion

'If we are to use the methods of science in the field of human affairs, we must assume that behavior is lawful and determined. We must expect to discover that what a man does is the result of specifiable conditions and that once these conditions have been discovered, we can anticipate and to some extent determine his actions. This possibility is offensive to many people. It is opposed to a tradition of long standing which regards man as a free agent, whose behavior is the product, not of specifiable antecedent conditions, but of spontaneous inner changes of course…. If we cannot show what is responsible for a man's behavior, we say that he himself is responsible for it. The precursors of physical science once followed the same practice, but the wind is not longer by Aeolus, nor is the rain cast down by Jupiter Pluvius.'

– Burrhus Skinner (1953, pp. 6-7, 283)

The main goal of the present thesis was to learn more about the role of endogenous and exogenous factors in goal-directed behavior by using the voluntary task switching (VTS) procedure. In various domains in experimental psychology, for example in the domains of cognitive control (e.g. Botvinick, Braver, Barch, Carter & Cohen, 2001), selective attention (e.g. Lavie, 2005; Yantis, 2000) and attention to action (e.g. Norman & Shallice, 1986), converging evidence was found that behavior is never driven exclusively by endogenous processes (top-down control) or by exogenous factors (bottom-up control), but is the result of an interplay between both. Results of a study by Arrington (2008) suggested that also a voluntary task choice is the result of an interplay between top-down and bottom-up control (e.g. Arrington, 2008).

In the present thesis four studies were described in which we investigated the role of these two control modes and how these can interact in voluntary task selection by manipulating the relative contribution of both within different experimental designs, procedures and by inducing different kinds of bottom-up control.

OVERVIEW OF THE FINDINGS

In *Chapter 2,* we investigated how different elements in the environment can guide a task choice. Mayr and Bell (2006) were the first to report that immediate stimulus repetitions can affect task choice in such a way that more tasks are repeated. As a method to investigate the mechanisms underlying this effect we introduced a concurrent working memory (WM) load when selecting tasks voluntarily. In a first experiment was found that the impact of stimulus repetitions was stronger with a concurrent WM load. On the basis of two follow-up experiments, we concluded that the effect of stimulus repetitions is caused by the fact that on a subset of the trials no new task is selected but a response is associatively triggered when the stimulus is repeated. The observation that the impact of these stimulus-response associations is stronger with a concurrent WM load indicates that a function of top-down control is to shield task selection from automatically triggered responses. In this study, it was also found that repetitions of task-irrelevant features can prime a task repetition and that a stimulus can prime the selection of a task through previously formed stimulus-task associations. In addition, in all three experiments, it was found that tasks were repeated more with than without a concurrent WM load. On the basis of this finding we argued that a WM load hampers the ability to overrule the natural tendency to repeat tasks.

In *Chapter 3,* we pursued three research goals. First, we tested the account that the generally observed task-repetition bias is directly related to the requirement to select tasks and to the experience that task switches are more difficult to perform than task repetitions. Second, we wanted to collect more evidence for the account, defended in *Chapter 2,* that the effect of a WM load on voluntary task selection is related to the fact that subjects are hampered in their ability to overcome task repetitions when WM is loaded. Third, we tested the account, elaborated in *Chapter 2,* that the effect of stimulus repetitions is related to the formation of stimulus-response associations when executing a task. In two experiments, where hands, but not tasks, had to be selected randomly, we found evidence in support of all three accounts by observing a) a tendency to alternate hands (contrasted with the typical tendency to repeat tasks), b) that a WM load did not affect the hand-selection proportions (contrasted with the effects of a WM load on task-selection proportions), c) and that stimulus repetitions only affected the proportion of hand repetitions in Experiment 1, where a task had to be performed with the selected hand. In Experiment 2, where also a hand was selected but no task had to be executed, no stimulus-response associations were formed and the stimulus-repetition effect disappeared.

In *Chapter 4,* we investigated the hypothesis that, in contrast with a single-registration methodology, as used in *Chapter 2*, a double-registration methodology provides a measure of top-down driven task choice uncontaminated by bottom-up intrusions. Because in double registration, a task has to be selected on presentation of a neutral probe, one can assume that this leads to a situation in which no external factors that can affect the task choice are present. In two experiments, we found evidence against this hypothesis by observing that sequences of preceding task-execution responses can bias the task choice. This indicates that new bottom-up effects are induced by using two responses per trial in double registration. In addition, the two experiments showed that the course of these sequential effects over different stimulus-probe intervals (SPIs) depends on whether SPI is manipulated as a between- or a within-subjects factor. This inconsistency suggests that the impact of top-down control, which is necessary to overcome bottom-up influences, can be strategically adapted.

In *Chapter 5*, we proposed a model of voluntary task selection in which we incorporated a) the requirement to produce random sequences, b) the consideration that experience with execution of the tasks (repetitions are easier than switches) are taken into account, and c) the possibility that bottom-up factors guide a task choice. This model assumes that task selection is based on an automatic retrieval of chains of task information from long-term memory (LTM). These chains are formed in the initial phase of the experiment. In *Chapter 5*, it was shown that the properties of task sequences construed by this chain-retrieval model provide an excellent fit of the properties of the observed task sequences. The chain-retrieval model needs three free parameters. A first parameter m corresponds to the maximal length of the retrieved chain, and is related to WM capacity. A second parameter p corresponds to the probability of a task repetition in the stored chains. When p is high the chance is higher that sequences with more repetitions will be retrieved. A third parameter r is related to bottom-up priming of a task repetition. In this chapter, some tests were included in which the importance of all three parameters was confirmed. In addition, evidence was found that the retrieved chains not only contain information about the tasks but also about the task transitions in the chain.

THEORETICAL IMPLICATIONS

WHAT MAKES VOLUNTARY TASK SELECTION SO EXCEPTIONAL?

In a growing number of studies investigating VTS, the task-selection proportions are considered to represent properties of the processes underlying a task choice (e.g. Arrington, 2008; Arrington & Logan, 2004; 2005; Kessler, Shencar, & Meiran, 2009; Liefooghe, Demanet, & Vandierendonck, in press; Mayr & Bell, 2006; Vandamme, Szmalec, Liefooghe, & Vandierendonck, in press; Weaver & Arrington, in press). However, to this day it was never investigated whether these proportions really represent exclusive features of a task choice. Especially in the frequently used single-registration procedure, in which each task is mapped onto a separate hand, it is possible that these proportions represent nothing more than random sequences of hand selections. Clearly, for the sake of the validity of the VTS procedure in the study of task-selection processes this issue needs to be investigated. In *Chapter 3,* hand-selection sequences were compared directly with the task-selection sequences of Experiment 1 of *Chapter 2*. The results showed that the typically observed repetition bias in VTS (e.g. Arrington & Logan, 2004) appeared exclusively when tasks were selected, while an alternation bias, which is a typical observation in human random generation of events, was observed when only hands were selected. In addition, we found that the effect of a concurrent WM load on the number of repetitions disappeared when hands were selected. Both findings support the idea that task-selection proportions and the manipulations that influence these proportions can be used to study task-selection processes. On the basis of the results of *Chapter 3* and *5* we argued that a distinctive property of selecting tasks over other events (such as hands) is that switching between tasks is perceived to be more difficult than repeating tasks and that this relative difference in outcome of a choice is taken into account when selecting a new task. In the chain-retrieval model proposed in *Chapter 5* the tendency to avoid task switches is represented by the size of parameter *p*.

THE INTERPLAY BETWEEN TOP-DOWN AND BOTTOM-UP CONTROL IN VOLUNTARY TASK SELECTION.

In the present thesis, we collected convincing evidence for the view that, independent of the procedure used, bottom-up factors always play a significant role in the task choice. In a recent study, Arrington (2008) found that bottom-up control contributed to the task choice more with short than with long preparation intervals. As an account for this interaction, she proposed a horse-race model for voluntary task selection. On the basis of the executive control theory of visual attention of Logan and Gordon (2001), she suggested that voluntary task selection depends on a race between the tasks activated by top-down control and tasks activated by bottom-up control. In this perspective, when the preparation interval is short and top-down control is less efficient, tasks activated by bottom-up control reach a selection threshold first, and guide the task choice.

The results of Experiment 1 of *Chapter 2* can be interpreted as support for the horse-race model by showing that stimulus repetitions affect task choice more with a concurrent WM load. Because other studies have shown that a WM load can reduce the efficiency of top-down control (Logan, 2004), this finding fits with the idea that tasks activated by bottom-up control reach the selection threshold first because top-down is hindered by the WM load. However, based on two additional experiments, we were able to conclude that stimulus repetitions do not prime tasks, but simple responses. In Experiments 2 and 3 of *Chapter 2*, it was observed that, the impact of other bottom-up factors, such as repetitions of task-irrelevant information and stimulus-task associations, are not affected by this load. This contrasts with the effect of stimulus repetitions, and suggests that top-down control in VTS is not involved when activating and selecting tasks, as proposed by Arrington (2008), but is especially necessary to shield task selection against automatic response tendencies that do not correspond with the activated task (see also Hübner & Druey, 2006). Possibly, this shielding function of top-down control in task selection can be related to findings in studies investigating visual selective attention (for a review see Lavie, 2005).

In these studies was found that automatically triggered irrelevant responses (for example, in the Erikson flanker task) were suppressed less efficiently when performed under a concurrent WM load. Recently, other parallels between voluntary task selection and selective attention were already discussed by Arrington and Yates (2009) and Weaver and Arrington (in press).

Evidence in support of Arrington’s (2008) horse-race model may have been present in Experiment 2 of *Chapter 4*, in the observation that response-sequence effects were stronger with shorter stimulus-probe intervals (SPIs). However, the results of Experiment 1 of *Chapter 4* seem to challenge this model by showing that the interaction disappears when the length of the SPIs was unpredictable and varied from trial to trial. This different course of the sequence effects with various SPIs over the two experiments indicates that the contribution of top-down control, which is necessary to shield task selection from bottom-up intrusions, can rely on strategic adaptations. In our view these results can be explained by the horse-race model when in this model is incorporated that the strength of top-down control is not only influenced by manipulations of the preparation interval but also by the use of strategies. Although it is difficult to trace which strategies really take part, it is possible that subjects are more motivated to invest top-down control when the length of SPI varies from trial to trial. Possibly, when in the initial phase of the experiment subjects experience that their investment of top-down control results in successful shielding on a part of the trials (e.g. when SPI is long) they can adopt a strategy to invest more top-down control in the entire block. Also in a study of Mayr and Bell (2006), where individual differences in task selection were investigated, evidence for strategic modulation of top-down control was reported.

On the basis of the estimated parameters of the chain-retrieval model in *Chapter 4* we also found evidence for an interplay between top-down and bottom-up control. We observed that the parameter *r*, which represents the probability that a task selection is interrupted by a bottom-up intrusion, is higher with shorter preparation intervals[1].

In sum, evidence in the present thesis suggests that top-down control is particularly involved when task choices are shielded against automatic responses. The present study also shows that strategic modulations of top-down control have to be taken into account when one wants to manipulate the contribution of top-down and bottom-up control. In our view the findings that top-down control can be influenced by strategies and that stimuli can prime a task independent of top-down control, are both examples of the flexibility of our cognitive system to deal with different situations when performing goal-directed behavior.

AUTOMATICITY IN GOAL-DIRECTED BEHAVIOR

Already in the early ages of psychology, James (1890) acknowledged that people can perform actions with little thought and conscious awareness, or in other words, automatically. In view of the conviction that top-down control is a limited resource, it seems reasonable that not every action or task that is performed has to appeal on these resources and that actions and tasks can be activated by a separate mechanism.

[1] We found further support for an interaction between top-down and bottom-up control when estimating the parameters of the chain-retrieval model on the task sequences in *Chapter 2*, in the no-load and load conditions. We observed that the parameter r was higher under load, replicating the finding that bottom-up control is stronger when top-down control is less efficient. We also observed that the p parameter increased under load. This suggests that subjects attach more importance to task repetitions in cognitive demanding situations. Finally, we observed that the parameter m was reduced under load, indicating that chains maintained in short term memory are shorter when WM was loaded. We did not report these analyses in the main text because it is difficult to draw strong conclusions based on the chain-retrieval model when applied on such short sequences as in *Chapter 2*.

Logan (1988) proposed a mechanism for automatic behavior in his *'instance theory of automatization'*. In this theory, it is assumed that when a task is performed, representations are formed in LTM, called instances, which consist of information about the stimulus and the response. In this theory, behavior is considered to be automatic when it relies on the retrieval of these stored instances from LTM and not on time consuming top-down processes. Another implication of this theory is that behavior can only be automatic when actions are trained with a particular stimulus.

More recently, in studies in social psychology, it was found that when a person repeatedly pursued the same goal within a particular environment, the representation of that goal, together with the action schemas necessary to achieve that goal, will become active in the same environment (Bargh, 1990). These findings led Bargh (1990) to introduce the *auto-motive model*. This model extends the instance theory by assuming that also the representation of a goal can become associated with a representation of a stimulus. Hence, according to the auto-motive model the 'trigger' that starts a goal into operation can be removed from top-down control when it is activated through these associations. Recently, in several studies in cognitive psychology, these ideas could also be confirmed with task goals by observing that these can be activated automatically by elements in the environment (Lau & Passingham, 2007; Mattler, 2003; Mayr & Bryck, 2007; Verbruggen & Logan, 2009) and by established associations between stimuli and task goals (Verbruggen & Logan, 2008; Waszak, Hommel, & Allport, 2003). In these studies evidence for automatically activated task goals was derived from performance data, and to this day it was never investigated whether these associations could actually trigger the selection of a task goal.

In the present thesis, evidence was found for the mechanisms proposed by Logan (1988) and Bargh (1990). In Experiment 1 of *Chapter 2*, we confirmed the finding of Mayr and Bell (2006) that subjects repeated tasks more when the stimulus was repeated. On the basis of this chapter we can conclude that the stimulus-repetition effect can be related to the formation of instances, including information of the stimulus and the response. In *Chapter 3,* we found that such instances or associations are only formed when a stimulus has to be translated in a response during task execution. The observation in *Chapter 2* that the influence of these instances was stronger when top-down control was less efficient, supports the idea that top-down control is necessary to shield behavior against the influences of instances that are irrelevant for the activated task goal.

Additionally, in Experiment 3 of *Chapter 2*, we observed that when a stimulus was learned in the context of a particular task goal in a training phase, this stimulus influenced the selection of that task goal in a following test phase. This result can be framed within the auto-motive model of Bargh (1990), in that it suggests that the trigger to select a particular task goal can be associated with a stimulus and that when this stimulus reappears the selection of this task is facilitated. Important to mention is that we avoided the influence of stimulus-response associations by using a different response modality in the training than in the test phase. We also observed that the impact of stimulus-task associations did not depend on the efficiency of top-down control. In our opinion, this indicates that the effects of bottom-up control on the task choice do not always have to be interpreted as failures of top-down control to shield intentional task choice. Especially the effects of stimulus-task associations can be seen as examples of the ability of our cognitive system to use past experiences with stimuli, stored in long term memory, to delegate task choice to the environment (for similar ideas see Mayr & Bryck, 2007).

It speaks for itself that this mechanism plays an important role in daily life. Imagine a situation in which a person is driving a car and is approaching a red light. When this person is an experienced driver and has learned by experience that one has to reduce speed in front of a red light, the task goal (e.g. reducing speed) will be automatically activated and the response rules (e.g. hit the break) will be retrieved without top-down control coming into play.

CHAIN RETRIEVAL IN GOAL-DIRECTED BEHAVIOR

Based on the finding that the size of the task-repetition bias correlates with the speed of task repetitions, Mayr and Bell (2006) suggested that subjects adopt a discrete-events strategy by inhibiting the most recently executed task. However, in *Chapter 5* we found strong evidence against these discrete events by observing that a model, in which task selection is based on chains of tasks retrieved from LTM, produces an excellent fit of observed task sequences. According to this chain-retrieval model the task-repetition bias is not directly caused by a failure to overcome the tendency to repeat tasks, but by the fact that chains with more repetitions are more likely to be retrieved. It was argued that chains with more task repetitions are preferred because they are easier to perform than chains with more task switches (see also *Chapter 3*). During the execution of the task activated by these chains, bottom-up triggered repetitions can boost the number of task repetitions even more.

The observation that task choice in VTS may be based on chains of elements retrieved from LTM, can be considered as an important finding, not only for voluntary task selection in specific, but also for goal-directed behavior in general. It shows that when people are trying to accomplish a high-order goal, which in VTS is to execute random sequences of tasks, information about the outcomes of past attempts to accomplish this goal, are stored in LTM. One can say that the cognitive system gives priority to more successful action plans when trying to accomplish a goal. This mechanism to learn about past choices is advantageous because it allows people to produce more efficient goal-directed behavior in the future. On a more general level this mechanism can also be related to the law of least mental effort, which states that the cognitive system will always try to find ways to avoid tasks or strategies asking for high levels of cognitive demand (Balle, 2002).

INTENTIONALITY IN VOLUNTARY TASK SWITCHING

On the basis of the results of *Chapter 2* and *4*, one can say that each time a bottom-up intrusion is overruled by top-down control, this task selection is intentional or voluntary. In this view, the intentional or voluntary act in VTS is not to activate what is 'willed' but to avoid behavior that is 'unwilled'. In *Chapter 5,* the strength of this intentional component of task selection is represented in the chain-retrieval model in the parameter *r*. In the framework of the model, one can say that the lower the *r* parameter, the more choices are intentional. This account can be related to the idea of Libet (1999), mentioned in *Chapter 1*. He argued that although intentional free will is not the cause of our behavior, it can still act as a veto over automatic activity. At first inspection, this idea implies that all other unshielded intrusions must be considered as unintentional behavior. However, in the viewpoint of compatibilists as Wegner (2002) or Dennett (2003), this is not always true. In a previous section we already argued that a task choice in VTS can be delegated to elements in the environment based on past experiences with those elements (see Experiment 3 of *Chapter 2*). In a compatibilist's view this is exactly what we should interpret as intentional behavior, because past experiences are taken into account when a new task is selected. In that perspective, only automatic responses that do not correspond with an activated task goal, as observed in Experiment 1 of *Chapter 2,* can be considered as unintentional behavior.

In *Chapter 5,* we assumed that all task selections in which bottom-up intrusions are successfully suppressed are based on the automatic retrieval of chains from LTM. Does this task-selection mechanism correspond with intentional behavior? To our account, it does not with the classical perspective of intentionality because tasks are selected on the basis of automatic retrieval of tasks and are thus not selected on the basis of an intentional act. However, this mechanism fits with the idea of intentionality in a compatibilist's perspective, because the mechanism proposed by the chain-retrieval model entails that past experiences are stored and are helping future goal-directed to be more efficient.

CONCLUSION

As already argued in the Introduction (*Chapter 1*) the issue whether a task choice can be considered as 'voluntary' in the VTS procedure depends on the perspective the concept of intentionality is approached with. In the present thesis, no evidence was found for intentional control in the classical sense, because in each situation subjects were confronted with, task choices were influenced by external factors. However, we found support for intentional control in a compatibilist's sense, in the ability of the cognitive system to use past experiences (e.g. stimulus-task associations, task chains) in order to be more efficient in future goal-directed behavior.

Importantly, we also showed that the task-selection proportions in VTS can be used to investigate the processes that are involved when a task is selected. With respect to the main research goal, we showed that the interplay between top-down and bottom-up control in voluntary task selection lies in the fact that top-down control is essential to shield the execution of a selected task goal from automatically triggered actions that do not correspond with that particular task goal. Finally, we found that the strength of top-down control in voluntary task selection can be modulated strategically.

In sum, this thesis clearly shows that the voluntary task switching procedure is a useful tool to investigate the mechanisms of our cognitive system that allow us to perform efficient goal-directed behavior.

INDICATIONS FOR FUTURE RESEARCH

This research did not only lead to some new theoretical considerations, it has also its limitations. In the next paragraph these limitations are discussed, together with some ideas for future research.

In our view, the main limitation of the VTS procedure we used, is that subjects are instructed to generate random sequences of tasks. This instruction was first used by Arrington and Logan (2004) in order to obtain a sufficient number of task-switch trials needed for the analyses of the response latencies. Indeed, in recent studies of Kessler et al. (2009) and Liefooghe, Demanet and Vandierendonck (in press), it was found that without this instruction subjects rarely switched tasks. In our view, this finding indicates that voluntary choices are only made when a high-order goal (random generation) has to be accomplished.

Many studies in the random generation literature have indicated that the concept of randomness is not well understood by people in general, and that different people can have very distinct ideas about randomness (e.g. Nickerson, 2002). Because of the randomness instruction in VTS, the production of random sequences of tasks can be considered as the high-order goal. In our view, because the high-order goal in this procedure is difficult to grasp, it makes it very difficult to extend our conclusions to other situations.

A second limitation of the VTS procedure and the random instruction concerns the ecological validity, because in daily life people are confronted very rarely with situations in which tasks have to be selected in a random fashion. A potential solution for both limitations is to adjust the VTS procedure in such a way that subjects have to accomplish a well-defined high-order goal and can choose the tasks (sub-goals) on a voluntary basis in order to accomplish that goal. A paradigm that can be useful in this perspective is the so-called ‘cooking breakfast task’ (e.g. Craik & Bialystok, 2006). In this task, subjects must remember to start and stop cooking a number of foods and try to accomplish that all the foods are ready at the same time (high-order goal). In our opinion, it would be very interesting to investigate the effects of stimulus-task and stimulus-response associations, as well as the formation of task chains in LTM in such a procedure.

A third limitation of the procedure used also is related to the ecological validity. We believe that if one wants to generalize the conclusions made in the present thesis towards free task choices in daily life, where typically more than two tasks can be selected, one also has to use more than two tasks in future studies.

A fourth limitation of the present thesis is that we did not account for individual differences in task selection behavior. Mayr and Bell (2006) suggested that different subjects can adopt different strategies, and maybe use different mechanisms when selecting tasks. A possible way to investigate this issue more thoroughly is to divide subjects in two groups based on their WM capacity. On the basis of the assumptions made in *Chapter 5*, one could predict that the estimated parameter *m*, related to the length of the retrieved chains, will be higher for subjects with a higher WM capacity. On the basis of Experiment 1 of *Chapter 2* one could also expect that the *r* parameter, which is related to bottom-up intrusions, will be higher with low-capacity subjects. Another possibility is that low-capacity subjects have more difficulty with switching between tasks and that as a consequence chains with more task repetitions will be preferred. In this perspective WM capacity could have an effect on the size of the *p* parameter, in a way that this parameter is higher with low-capacity subjects.

The finding in *Chapter 2* that the general level of top-down control in task selection was higher when tasks were selected with a concurrent WM load raises the question if it is also possible to manipulate top-down control from trial to trial. In *Chapter 4* was found that trial-to-trial variations of the length of the preparation interval did not lead to variations in top-down control because of strategic adaptation. An alternative approach to investigate trial-to-trial variations of top-down control can be found in studies investigating post-error and post-conflict adaptation of top-down control. In these studies was found that the efficiency of top-down control to shield behavior against bottom-up intrusions was increased following trials which involved a response conflict or following response errors (e.g. Botvinick, Cohen, & Carter, 2004). These effects could be investigated in VTS when using tasks in which strong response conflicts are induced or when using difficult tasks in which a large amount of errors is made. On the basis of the present thesis, one could hypothesize that the influence of bottom-up triggered responses would be reduced following an error or following a response conflict. Because subjects made very few errors in the experiments described in the present thesis, this issue could not be investigated yet.

Another approach to dissociate internally driven from externally driven task choice in VTS is to dissociate these components on a functional-neuroanatomical level. Recent research in the domain of intentional action suggests that different systems might be involved in internally guided and environmentally guided control of behavior (Brass & Haggard, 2008; Waszak et al., 2005). The fronto-median cortex is related to internal components of action and the fronto-lateral cortex is crucial for externally guided action. There are only two brain-imaging studies that investigated intentional control in the context of VTS. Forstmann, Brass, Koch and von Cramon (2006) observed that the rostral cingulate zone in the medial pre-frontal cortex was more active with internally driven task selection compared to a situation in which the tasks were cued. Furthermore, a pattern classification study by Haynes et al. (2007) showed that internally driven task choice could be best predicted from anterior medial prefrontal cortex, supporting the idea that voluntary task selection is related to the fronto-median cortex. In our view, these studies could serve as a starting point to investigate the interplay of top-down control and bottom-up control in voluntary task selection using functional magnetic resonance imaging.

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NEDERLANDSE SAMENVATTING

ROL VAN ENDOGENE EN EXOGENE FACTOREN BIJ HET ZELF-GEGENEREERD WISSELEN TUSSEN TAKEN

INLEIDING

Zoals de titel aangeeft had deze thesis als doel de rol van endogene en exogene controle te onderzoeken in situaties waar mensen vrijwillig kunnen kiezen tussen verschillende taken. Het begrip endogene controle kan vergeleken worden met de invloed van interne processen op het gedrag, terwijl het begrip exogene controle kan vergeleken worden met de invloed op het gedrag door elementen uit de omgeving. In deze thesis werd de rol van deze vormen van controle op een taakkeuze onderzocht met behulp van de procedure van de vrijwillige taakafwisseling (VTA). Deze procedure werd oorspronkelijk ontwikkeld door Arrington en Logan (2004) om na te gaan of de zogenaamde taakwisselkost, die het verschil in prestatie tussen het herhalen van taken en het wisselen tussen taken uitdrukt, ook optreedt als de taakkeuze vrij is. In andere studies, waar cues gebruikt werden om aan te geven welke taak uitgevoerd moet worden, werd namelijk ontdekt dat de wisselkost niet door endogene controle, die nodig is om te wisselen tussen taken, werd veroorzaakt, maar door het wisselen van de cues zelf (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). Niettegenstaande deze bevinding vonden Arrington en Logan (2004) met de VTA procedure, dus zonder het gebruik van taakcues, nog steeds een taakwisselkost. Dit suggereert dat deze procedure een goede meting oplevert van de interne processen (endogene controle) die nodig zijn om te wisselen tussen taken (zie ook Liefooghe, Demanet, & Vandierendonck, 2009; in press).

Een ander voordeel van de VTA procedure is dat niet enkel de prestatie op een bepaalde taak onderzocht kan worden, zoals de reactietijd of de accuraatheid, maar ook de taakkeuze zelf. In een aantal studies die deze taakkeuze onderzochten met behulp van de VTA procedure, kwam men tot de opmerkelijke bevinding dat een vrijwillige taakkeuze sterk beïnvloed wordt door externe factoren (e.g. Mayr & Bell, 2006). Men zou kunnen stellen dat een vrijwillige taakkeuze toch niet zo 'vrijwillig' is als verondersteld werd. In een recente studie van Arrington (2008) werd ontdekt dat hoe minder sterk de impact van endogene controle was, hoe sterker de invloed van de exogene controle werd. In dit doctoraat zetten we deze onderzoekslijn verder en onderzochten we de interactie tussen endogene en exogene controle in verschillende situaties en procedures, alsook door het introduceren van verschillende exogene factoren.

OVERZICHT VAN DE BEVINDINGEN

In *Hoofdstuk 2* hebben we onderzocht hoe verschillende externe factoren een taakkeuze kunnen beïnvloeden. Mayr en Bell (2006) observeerden als eerste dat het herhalen van de doelstimulus de taakkeuze beïnvloedt. Zo werden taken meer herhaald wanneer de stimulus herhaald werd. Om de efficiëntie van endogene controle te manipuleren, vroegen we proefpersonen om vrijwillig te wisselen tussen taken terwijl hun werkgeheugen werd belast. In een eerste experiment vonden we dat de invloed van stimulusherhalingen groter was mét dan zonder een wergeheugenbelasting. In twee daaropvolgende experimenten vonden we dat een taakkeuze ook beïnvloed kan worden door het herhalen van taak-irrelevante stimuli, alsook dat een stimulus een taakselectie kan uitlokken door vooraf gevormde stimulus-taak associaties. Deze effecten werden bovendien niet beïnvloed door de geheugenbelasting. Uit deze bevindingen konden we besluiten dat het effect van stimulusherhalingen veroorzaakt werd door associaties die gevormd werden tussen een stimulus en de respons op deze stimulus. De bevinding dat dit effect sterker is met een geheugenbelasting wijst er op dat endogene controle een belangrijke functie heeft bij het afschermen van een vrijwillige taakkeuze tegen automatisch uitgelokte responsen. In de drie experimenten bleek bovendien dat taken meer herhaald werden mét dan zonder een geheugenbelasting. Dit wijst er op dat door een geheugenbelasting, de endogene controle die verantwoordelijk is om de natuurlijke tendens om taken te herhalen tegen te gaan, minder efficiënt wordt.

In *Hoofdstuk 3* onderzochten we drie hypotheses. Ten eerste onderzochten we of de algemene tendens om taken te herhalen gerelateerd is aan de bevinding dat het wisselen tussen taken moeilijker is dan taken te herhalen. Ten tweede onderzochten we de hypothese, die verdedigd werd in *Hoofdstuk 2*, dat het effect van een geheugenbelasting op de taakkeuze verband houdt met een verminderd vermogen om taakrepetities te vermijden wanneer endogene controle minder sterk is. Ten derde testten we de hypothese dat de bevinding gerapporteerd in *Hoofdstuk 2*, namelijk dat stimulusherhalingen taakherhalingen uitlokken, veroorzaakt wordt door het vormen van stimulus-respons associaties tijdens het uitvoeren van een taak. In twee experimenten, waar geen taken maar handen random geselecteerd dienden te worden, werd iedere hypothese bevestigd door de bevindingen dat (1) er een tendens is om tussen handen te wisselen (in tegenstelling tot een tendens om taken te herhalen), (2) een geheugenbelasting geen effect heeft op de handkeuze (in tegenstelling tot een taakkeuze), en (3) stimulusherhalingen enkel de handkeuze beinvloeden wanneer een taak uitgevoerd moet worden met de geselecteerde hand.

In *Hoofdstuk 4*, onderzochten we de hypothese dat, in tegenstelling tot een procedure met een enkele registratie, zoals gebruikt in *Hoofdstuk 2*, een procedure met een dubbele registratie een meer accurate meting van vrijwillige taakkeuze oplevert, die bovendien niet beïnvloed wordt door exogene factoren. Deze hypothese steunt op de veronderstelling dat, doordat bij dubbele registratie een taak geselecteerd moet worden bij het verschijnen van een neutrale probe, er geen externe factoren aanwezig zijn die de taakkeuze kunnen beïnvloeden. In twee experimenten vonden we evidentie tegen deze hypothese. We vonden namelijk dat sequenties van voorafgaande acties een taakkeuze beïnvloeden. Deze bevinding impliceert dat wanneer er twee responsen per trial moeten worden gegeven, er nieuwe sequentiële effecten ontstaan die de taakkeuze beïnvloeden. Bovendien vonden we in deze twee experimenten dat het verloop van deze sequentiële effecten over stimulus-probe intervallen (SPIs) met een verschillende lengte, afhankelijk is van de manier waarop de lengte van de SPI werd gemanipuleerd, namelijk als een binnen- of tussen-subject factor. Deze bevinding toont aan dat tijdens het selecteren van taken, de impact van endogene controle, die nodig is om externe invloeden te onderdrukken, door het gebruik van strategieën kan worden beïnvloed.

In *Hoofdstuk 5* werd een model ontwikkeld voor vrijwillige taakkeuze. In dit model werd verondersteld dat een vrijwillige taakkeuze gebaseerd is op een automatische activatie van ketens van taakgerelateerde informatie, opgeslagen in het lange termijn geheugen (LTG). Het zogenaamde ‘chain-retrieval’ model hield bij het produceren van taak sequenties rekening met drie parameters. Een eerste parameter, *m*, komt overeen met de maximale lengte van een geactiveerde keten van taken uit het LTG, en is gerelateerd aan de werkgeheugencapaciteit van de proefpersoon. Een tweede parameter, *p*, komt overeen met de proportie taakherhalingen in een in het LTG opgeslagen keten. Als *p* groot is, is ook de kans groter dat ketens met meer taakherhalingen worden geactiveerd. Een derde parameter, *r*, stelt de kans voor dat een taakkeuze door een externe factor uitgelokt wordt. We konden aantonen dat de eigenschappen van de sequenties van taken, zoals voorspeld door het model, zeer goed overeenkomen met de eigenschappen van de taak sequenties die gevolgd werden door de proefpersonen. Het model heeft bijgevolg een zeer goede fit in vergelijking met andere modellen.

CONCLUSIE

Op basis van deze thesis kunnen we stellen dat het interpreteren van een taakkeuze als ‘vrijwillig’, afhankelijk is van het perspectief waaruit men het concept ‘intentionele controle’ benadert. We vonden in deze thesis dat proefpersonen bij het kiezen van een taak, in elke situatie worden beïnvloed door verschillende externe factoren.

Zelfs wanneer een keuze niet wordt beïnvloed door externe factoren, vonden we in het ‘chain-retrieval’ model evidentie dat onze ‘vrijwillige’ taakkeuze gestuurd wordt door automatische activatie van informatie uit het lange termijn geheugen. Deze bevindingen pleiten tegen de aanwezigheid, in the VTA procedure, van intentionele controle in de klassieke betekenis, waarbij gesteld wordt dat keuzes worden gemaakt op basis van een eigen beslissing en niet gestuurd worden door automatische invloeden (uit de omgeving of door ons verleden). Anderzijds kunnen we intentionele controle bekijken als de mogelijkheid om vorige ervaringen op te slaan en deze te gebruiken om meer efficiënt te handelen in toekomstig doelgericht gedrag (zie Dennett, 2003). Zowel de bevinding dat stimulus-taak associaties worden gevormd, als het geheugen-mechanisme geïntroduceerd in het 'chain-retrieval' model, vormen vanuit dit perspectief evidentie voor intentionele controle.

Met betrekking tot de belangrijkste onderzoeksvraag vonden we in deze thesis evidentie voor een interactie tussen endogene en exogene controle bij het vrijwillig selecteren van taken. We konden aantonen dat endogene controle belangrijk is om tijdens het uitvoeren van een geselecteerde taak, automatisch uitgelokte acties die niet rijmen met deze taak, te kunnen onderdrukken. Ook konden we aantonen dat de invloed van deze endogene controle strategisch gemoduleerd kan worden.

Tot slot kunnen we op basis van deze thesis ook besluiten dat de procedure van de vrijwillige taakafwisseling een zeer goed instrument is om de flexibiliteit van ons cognitief systeem, wat ons toelaat om efficiënt doelgericht gedrag te kunnen stellen, te onderzoeken.

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