Effects of Rule Uncertainty on Cognitive Flexibility in a Card-Sorting Paradigm

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Abstract

Cognitive flexibility has been studied in two separate research traditions. Neuropsychologists typically rely on rather complex assessment tools such as the Wisconsin Card Sorting Test (WCST). In contrast, task-switching paradigms are used in experimental psychology to obtain more specific measures of cognitive flexibility. We aim to contribute to the integration of these research traditions by examining the role of the key factor that differs between the WCST and experimental task-switching paradigms: rule uncertainty. In two experimental studies, we manipulated the degree of rule uncertainty after rule switches in a computerized version of the WCST. Across a variety of task parameters, reducing rule uncertainty consistently impaired the speed and accuracy of responses when the rule designated to be more likely turned out to be incorrect. Other performance measures such as the number of perseverative errors were not significantly affected by rule uncertainty. We conclude that a fine-grained analysis of WCST performance can dissociate behavioural indicators that are affected vs. unaffected by rule uncertainty. By this means, it is possible to integrate WCST results and findings obtained from task-switching paradigms that do not involve rule uncertainty.

Keywords: Wisconsin Card Sorting Test; cognitive flexibility; executive functioning; task switching; cognitive control; uncertainty

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Cognitive flexibility allows for the efficient adaptation of goal-directed behaviour to changing environmental demands (Garcia-Garcia, Barceló, Clemente, & Escera, 2010) and has thus been proposed to be a core component of executive functioning (Miyake et al., 2000). The construct of cognitive flexibility has attracted interest from both neuropsychologists and researchers in the field of experimental psychology.

Neuropsychologists typically rely on rather complex assessment tools such as the Wisconsin Card Sorting Test (WCST, Berg, 1948; Grant & Berg, 1948; Heaton et al., 1993) to study cognitive flexibility in clinical populations. The WCST requires participants to sort cards and to use the experimenter's feedback to shift between different sorting rules. Individuals with damage to the frontal lobes (Demakis, 2003; Milner, 1963) or to the basal ganglia (Eslinger & Grattan, 1993) as well as patients with a variety of neurological and psychiatric diseases (Kudlicka, Clare, & Hindle, 2011; Lange, Brückner, Knebel, Seer, & Kopp, in press; Lange, Seer, Salchow et al., 2016; Lange, Vogts et al., 2016; Roberts, Tchanturia, Stahl, Southgate, & Treasure, 2007; Romine et al., 2004; Shin, Lee, Kim, & Kwon, 2014; Snyder, 2013) have been shown to have considerable difficulties with the task demands associated with the WCST. However, the interpretation of these findings is complicated by the task impurity of the WCST (Miyake & Friedman, 2012; Strauss, Sherman, & Spreen, 2006). As the WCST confounds a variety of different cognitive processes (Dehaene & Changeux, 1991; Ridderinkhof, Span, & van der Molen, 2002), WCST performance deficits cannot unequivocally be attributed to impaired cognitive flexibility (Cools, Barker, Sahakian, & Robbins, 2001).

Avoiding the complexity issues associated with the WCST, experimental psychologists have developed variants of the task-switching paradigm as a more process-pure alternative for the study of cognitive flexibility (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). These paradigms involve switching between different mental operations (e.g., indicating whether a number is smaller or larger than five vs. indicating whether a number is odd or even) after a fixed number of task repetitions (alternating-runs paradigm), in response to task cues (task-cuing paradigm), or at the discretion of the participant (voluntary task switching). Research using task-switching paradigms has revealed a wide range of insights into the mechanisms contributing to cognitive flexibility in the healthy mind (Grange & Houghton, 2014; Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010).

Unfortunately, although clinical neuropsychology and experimental psychology share their interest in the concept of cognitive flexibility, these two research traditions have remained largely unintegrated. The few studies that have attempted integration focused on the commonalities between the WCST and task-switching paradigms on the performance level (Gamboz, Borella, & Brandimonte, 2009; Miyake et al., 2000) or on level of neural activation (Buchsbaum, Greer, Chang, & Berman, 2005). Here, we adopt a different approach to bridging the two literatures by examining those task characteristics that differ between the WCST and experimental task-switching paradigms.

We argue that the critical factor distinguishing the WCST from the majority of task-switching paradigms is rule uncertainty. Both the WCST and task-switching paradigms require participants to apply one task rule on some trials (e.g., match cards by colour; categorize numbers based on magnitude) and to apply a different task rule on other trials (e.g., match cards by shape; categorize numbers based on parity). However, in contrast to task-switching paradigms, the WCST involves two important characteristics whose combination entails that participants cannot always be certain about the currently valid task rule. First, examinees performing the WCST have to shift between three different task rules (i.e., matching cards according to colour, shape, or number), whereas most task-switching paradigms involve only two viable rules. Second, changes of the valid WCST rule are communicated via implicit transition cues (i.e., the examinee is informed that the applied sorting rule is not correct and thus needs to be changed), which do not specify the rule to which participants should switch. In contrast, most cued task-switching paradigms use task cues, which explicitly state the rule that should be applied on the upcoming trial. While several task-switching studies have used more than two task rules (Buchler, Hoyer, & Cerella, 2008; Emerson & Miyake, 2003; Kessler & Meiran, 2010; Rubin & Meiran, 2005; Kleinsorge & Apitzsch, 2012; Kleinsorge & Scheil, 2015; Kray, Li, & Lindenberger, 2002; Souza, Oberauer, Gade, & Druey, 2012) or transition-cuing procedures (Chevalier, Wiebe, Huber, & Andrews Esby, 2011; Forstmann, Brass, & Koch, 2005; Reuss, Kiesel, Kunde, & Hommel, 2011; Saeki & Saito, 2009; Schneider & Logan, 2007; Van Loy, Liefooghe, & Vandierendonck, 2010; West, Langley, & Bailey, 2011) in the past, it is only the combination of these two characteristics that gives rise to rule uncertainty on the WCST (Kopp & Lange, 2013). When being cued to switch away from an incorrect rule on the WCST, examinees do not have any information as to which of the remaining two rules might be the correct one. This uncertainty about the correct rule may affect the cognitive processes that allow switching from one rule to another (Kopp & Lange, 2013; Lange, Seer, Finke, Dengler, & Kopp, 2015; Barceló, Escera, Corral, & Periáñez, 2006; Barceló, Periáñez, & Nyhus, 2008).

To integrate the neuropsychological literature using the WCST and the experimental literature using task-switching paradigms, it is thus necessary to understand the contributions of rule uncertainty to WCST performance. One possibility to manipulate the degree of rule uncertainty associated with rule switches on the WCST involves varying the number of WCST rules (Kopp & Lange, 2013; Lange, Kröger et al., 2016; Lange, Lange et al., 2016). However, by changing the number of rules one does not only manipulate rule uncertainty but also confounded factors such as working memory load or the need for concept learning. Here, we present an alternative manipulation that allows examining which aspects of WCST performance are affected by rule uncertainty.

In a recent study using a computerized version of the WCST (the cWCST), we (Lange, Seer, Müller, & Kopp, 2015) informed participants that one of the three standard WCST rules was more frequent than the other two rules. This global information about rule frequencies allowed participants to know that, after a switch away from the more frequent rule, the remaining two rules were equally likely to be correct (high rule uncertainty). In contrast, after a switch away from one of the two less frequent rules, the more frequent rule was more likely to be correct (i.e., in 70% of the trials) than the alternative rule (low rule uncertainty). Although our previous study focused on the psychophysiological correlates of rule uncertainty on the cWCST, the associated behavioural data already provided some insights into the uncertainty-related differences between the WCST and task-switching paradigms.

First, as compared to situations with reduced rule uncertainty, switching to a rule in the high-uncertainty condition was associated with a considerable increase in response latencies. Because of the chosen conditional probabilities, not all rule switches resulted directly in the correct identification of the valid task rule. On a subset of trials, participants were informed that they had selected the wrong rule and thus that they had to perform an additional switch to get to the currently valid rule. We referred to these trials as *addendum switch trials*. Participants were faster and more accurate in switching to the valid rule on the addendum switch trial in the high-uncertainty condition as opposed to the low-uncertainty condition. In other words, reducing the rule uncertainty that is typically associated with the WCST accelerated responses on switch trials, but decelerated addendum switches when the rule chosen on the switch trial proved to be invalid. Reduced rule uncertainty might thus induce an increased commitment to the more likely rule on the switch trial which has to be overcome at the expense of increased performance cost on the addendum switch trial. In contrast, some cWCST counterparts of traditional WCST measures (such as the number of perseverative errors or the number of set-loss errors) did not seem to be affected by our manipulation of rule uncertainty.

The aim of the present studies was threefold. First, we wanted to replicate the behavioural evidence for rule-uncertainty effects on the cWCST presented by Lange, Seer, Müller, and colleagues (2015). Second, we aimed at testing potential moderators and boundary conditions of these effects, which might be of particular interest to experimental psychologists studying cognitive flexibility using task-switching paradigms. Third, we increased our focus on traditional WCST measures to highlight the implications of rule-uncertainty effects for the interpretation of neuropsychological WCST data.

Study 1

Study 1 was designed to replicate and extend the results of Lange, Seer, Müller, and colleagues (2015). Specifically, we aimed at a more detailed understanding of rule-uncertainty effects on cWCST performance by examining the role of two potential moderators. On the one hand, we manipulated the likelihood of the more likely rule in low-uncertainty conditions. While this likelihood was set to a constant 70% in our previous study (Lange, Seer, Müller et al., 2015), it varied block-wise between 60% and 80% in Study 1. By means of this manipulation, we explored whether larger reductions of rule uncertainty lead to larger effects on cWCST performance. Stronger rule-uncertainty effects in the 80% condition would indicate that participants use the globally provided numeric likelihoods to differentially commit to the more likely rule on switch trial. On the other hand, we manipulated the amount of preparation time given to participants between the onset of feedback cues and the onset of target displays (i.e., the cue-target interval, CTI). It is commonly assumed that, at long CTIs, some of the processes that are required to execute a switch from one rule to another can already be completed before target onset (Kiesel et al., 2010). This preparatory component of switching is often linked to active processes of task-set reconfiguration. In contrast, passive processes of task-set inertia have been proposed to account for the residual component of switching, that is, the component that is unaffected by CTI length (Meiran, 2000). Analysing the potential effect of CTI length on rule-uncertainty effects in the cWCST might thus reveal which kind of processes (active task-set reconfiguration vs. passive task-set inertia) are affected by rule uncertainty.

Methods

Participants. Twenty-five university students (18 female; 7 male; mean age = 22.16 years, SD = 3.59 years) with normal or corrected-to-normal vision participated for course credit. The reported study has been approved by the Ethics Committee of Hannover Medical School and was carried out in accordance with the approved protocol. Informed consent was obtained from all participants.

We initially aimed at a target sample size of 24. Due to overbooking, we tested two additional participants. One poorly performing participant was excluded because of the absence of valid trials in some cells of our experimental designs. Averaged across conditions, this participant committed 35% perseverative errors on switch trials, 77% errors on addendum switch trials, and 17% errors on repetition trials. The target sample size was determined to be similar to other studies in the field (see Lange, Seer, Müller et al., 2015) rather than being based on an explicit a priori power analysis. However, a power analysis based on the results presented by Lange, Seer, Müller, and colleagues (2015) reveals that Study 1 had sufficient power to detect the effects reported in our previous study. In that study, we reported three behavioural effects of rule uncertainty on cWCST performance: Reduced rule uncertainty accelerated response latencies on switch trials, $\eta_p^2 = .47$, prolonged response latencies on addendum switch trials, $\eta_p^2 = .48$, and increased error rates on addendum switch trials, $\eta_p^2 = .39$. Power analysis (G*Power 3.1.9.2, Faul, Erdfelder, Lang, & Buchner, 2007) indicates that the smallest of these effect sizes can be detected with a likelihood of 96% given $N = 25$ and $\alpha = .05$.

Task. We used an established version of the cWCST (e.g., Barceló, 2003; Lange, Seer, Finke et al., 2015; Lange, Kröger et al. 2016). The task was designed using the

Presentation® software (Neurobehavioral Systems, Albany, CA). Stimuli were presented against the white background of a 15.3 inch notebook screen. Unless otherwise noted, the task parameters of this version did not differ from the parameters of the cWCST version used by Lange, Seer, Müller, and colleagues (2015).

Participants were required to match cards according to one of three possible sorting rules (colour, shape, number), with the valid sorting rule changing after a variable number of trials. Target displays consisted of four key cards which appeared invariantly above one stimulus card, all configured around the centre of the computer screen (Figure 1). Stimulus cards varied on three dimensions (colour: red, green, yellow, blue; shape: triangle, star, cross, circle; number of objects: one, two, three, four), and these dimensions equalled the three viable task rules. As each stimulus card shared exactly one unique stimulus feature with three out of the four key cards, the applied sorting rule could unambiguously be identified (Barceló, 2003; Nelson, 1976).

Participants were instructed that their task would be to match the stimulus card with one of the four key cards in accordance with the currently valid rule. They sorted the cards by pressing one of four keys (‘<‘, ‘y‘, ‘.’, ‘-‘) on a QWERTZ notebook keyboard that were mapped to the spatial position of the key cards on the screen. Target displays remained on screen until a key was pressed.

Responses were followed by the presentation of a feedback cue. Feedback cues indicated whether participants needed to change the previously applied sorting rule on the upcoming trial (Kopp & Lange, 2013; Lange, Seer, Loens et al., 2016). We used word stimuli, written in Arial 31 and presented in the centre of the screen, to inform participants that they should repeat the previously executed rule (“REPEAT”, “STAY”; implying that the previously applied rule was correct) or that they should switch to a different rule (“SWITCH”; implying that the previously applied rule was not correct). Our choice to use cWCST feedback cues focusing on the required rule transition (as opposed to traditional WCST feedback that focuses on the correctness of the previous response) is historically grown. In a study in healthy young participants (Kopp & Lange, 2013), we did not find any differences in behavioural or neural responses between conditions that employed correctness (correct/wrong) vs. transition (repeat/switch) wording. In our neuropsychological studies in samples of older or diseased patients (Lange, Seer, & Kopp, 2017), we then wanted to avoid that poorly performing individuals were continuously confronted with negative valence feedback (i.e., “WRONG”). Hence, we decided to use the more neutrally worded transition feedbacks in all our cWCST studies from that point onwards, including our study on rule-uncertainty effects (Lange, Seer, Müller et al., 2015). Two different repetition cues were used to separate the contributions of rule switching and cue switching (Mayr & Kliegl, 2003). If we had used only one repetition cue (e.g., “REPEAT”), a repetition of the correct task rule would always have involved a cue repetition from the previous (“REPEAT”) to the current (“REPEAT”) trial. In contrast, rule switches necessarily involve a cue switch from the previous (“REPEAT”) to the current (“SWITCH”) trial. This confound can be eliminated by introducing rule repetitions that involve a cue switch as well (i.e., “REPEAT” on the previous trial followed by “STAY” on the current trial). However, as the comparisons here are not affected by the confound of rule switching and cue switching, and as cue switching did not interact with any of the independent variables in any of our studies, we decided to omit this factor in our report for the sake of clarity.

The valid task rule changed after a run of rule repetitions. The number of rule repetitions after a rule change was drawn from an exponential distribution to ensure that rule changes remained unpredictable to participants (Altmann, 2004). Run lengths varied between two and eight repetitions. Note that the average run length (i.e., three repetitions) was slightly shorter than in the study by Lange, Seer, Müller, and colleagues (2015; 3.5 repetitions per run). Participants completed four blocks of cWCST trials, each consisting of 72 runs and a short break after the first 36 runs.

Design and procedure. Rule changes were associated with either high rule uncertainty or low rule uncertainty. After a rule switch in the high-uncertainty condition, participants had to choose between two rules that were equally likely to be correct. After a rule switch in the low-uncertainty condition, participants had to choose between one rule that had a high likelihood of being correct and one rule that had a low likelihood of being correct. These likelihoods of being the correct rule were manipulated between blocks: In two blocks, the more likely rule had a 80% chance of being correct, whereas in the other two blocks, the more likely rule had a 60% chance of being correct (see Figure 2). The two blocks corresponding to each of the likelihood conditions were presented in direct succession with the order of likelihood conditions being counterbalanced across participants.

As a result of this manipulation of conditional rule likelihoods, one of the three cWCST rules was more frequent than the other two. The more frequent rule (i.e., colour, shape, or number) was held constant across conditions for each participant and counterbalanced across participants. To ensure that the experienced rule likelihoods corresponded to the instructed rule likelihoods, we created a pseudorandomized sequence of frequent-rule runs and less-frequent-rule runs for each block that was to be completed by each participant.

CTI length was manipulated between blocks as well. In two blocks, feedback-cue onset preceded target-stimulus onset by 1200 ms, whereas in the other two blocks, CTI was set to 300 ms. To avoid confounding of active preparation and passive inertia effects, the response-target interval (RTI) was held constant (at 1500 ms) across blocks by inversely manipulating the response-cue interval (RCI; Kiesel et al., 2010). In the CTI = 1200 ms blocks, RCI was set to 300 ms, whereas in the CTI = 300 ms blocks, RCI was set to 1200 ms. Cue-presentation time was 200 ms. The order of CTI blocks within the grouped rule likelihood blocks was counterbalanced across participants.

Prior to each block, participants were given the opportunity to practice the task. During the practice, participants first completed five runs under explicitly instructed standard WCST rule likelihoods (i.e., all three rule were equally frequent) and under the CTI and RCI settings of the upcoming block. They were then informed about the more frequent rule and about the rule likelihoods in the upcoming block and were given another five runs to practice the task under these conditions.

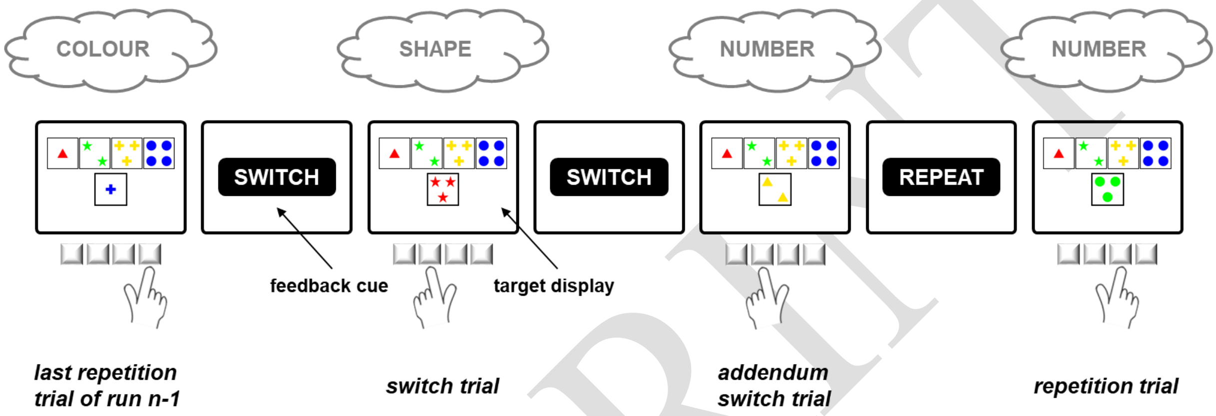

Figure 1. Different types of trials and the dynamics of rule transitions on the computerized Wisconsin Card Sorting Test. Thought clouds display the rule that a hypothetical participant currently believes to be correct (and thus applies). From left to right: The hypothetical participant applies the colour rule on the last repetition trial of the previous run. In this run (not displayed here), sorting cards according to the colour rule has repeatedly resulted in the presentation of repeat feedback. The participant thus justifiably assumes that colour is still the correct rule (see thought cloud). However, the switch feedback cue in response to applying the colour rule now signals that this rule is no longer correct. Hence, on the next trial (i.e., the switch trial), the participant needs to switch to another rule. The participant chooses the shape rule, but the subsequent presentation of another switch feedback cue signals that this is not the newly correct rule. The participant has to switch rules again on the next trial (i.e., the addendum switch trial) and decide to apply the number rule. Number is the correct new rule

as indicated by the subsequent repeat feedback cue. The participant is now expected to repeat this rule on the next trial (i.e., the repetition trial).

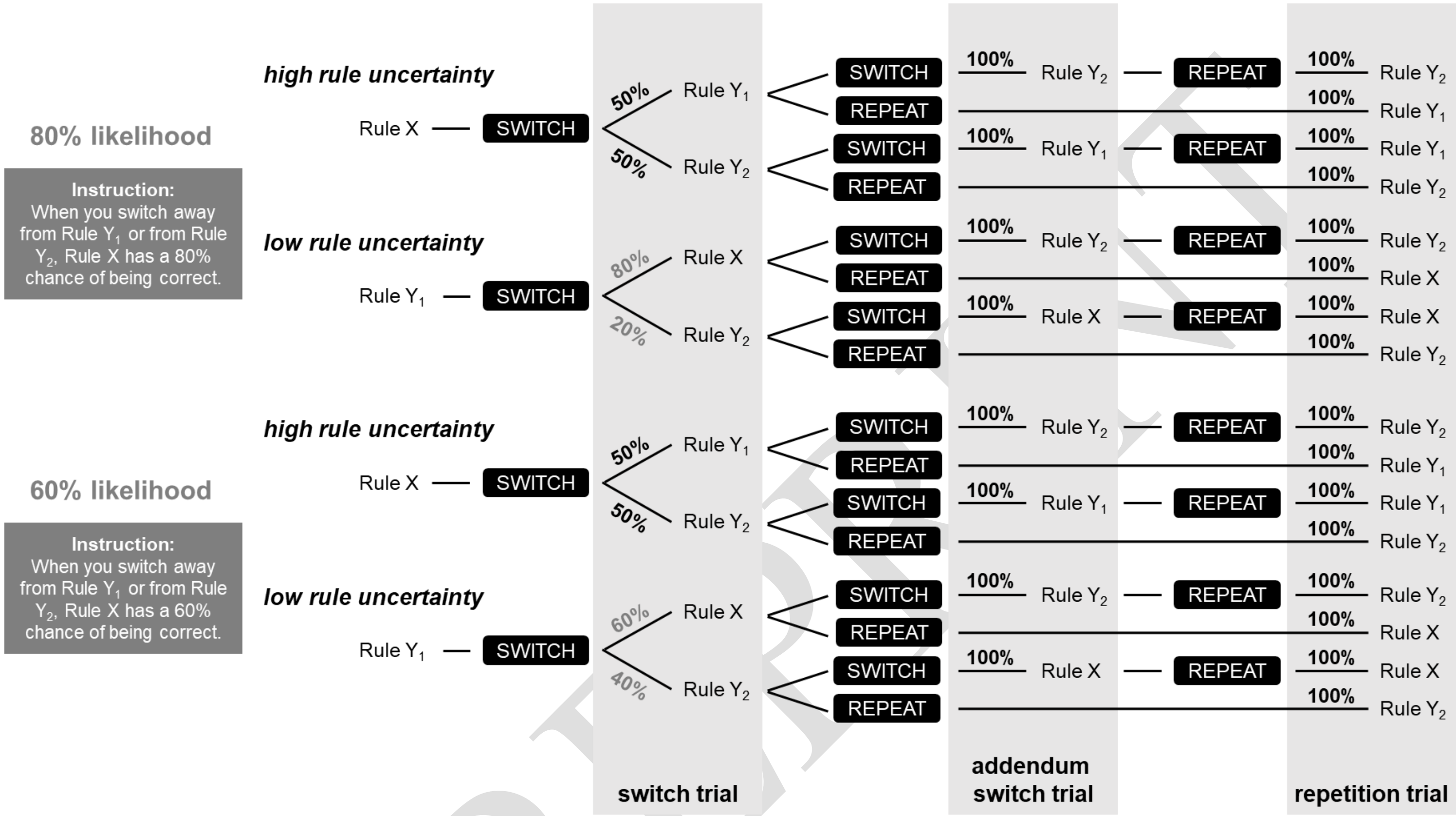

Figure 2. Experimental design of Study 1. The factors trial type (switch, addendum switch, repetition) and rule uncertainty (high, low) vary within a block while the factor likelihood (60%, 80%) is manipulated between blocks. Percentages denote conditional rule probabilities. Note that addendum switch and repetition trials in the high-uncertainty condition did not involve more uncertainty than in the low-uncertainty condition. Our manipulation of rule uncertainty exclusively pertains to the uncertainty involved when choosing between rules on the switch trial.

Data analysis. We distinguished between three different trial types: switch trials, addendum switch trials, and repetition trials (Figure 1 & 2). Switch trials involved the instruction to switch away from a task rule that had successfully been applied on the previous trial. As stated above, the valid cWCST rule was changed in an unpredictable manner and participants were not prospectively informed about an upcoming change in task rules. When participants continued to apply a previously correct rule after the valid task rule had been changed, their response resulted in the presentation of a switch feedback cue. The trial following the presentation of this switch feedback cue is referred to as *switch trial*. When participants did not switch to the correct rule on the switch trial, they encountered another switch feedback cue, informing them that they had to switch task rules again. The trial following the presentation of this second switch feedback cue is referred to as *addendum switch trial*. Integrating the feedback received on the switch trial and on the addendum switch trial allows excluding two of the three viable rules and thus inferring the correct new rule (Lange, Kröger, et al., 2016). When participants switched to the correct task rule, their sorting response resulted in the presentation of a repeat feedback cue. The trial following the presentation of this first repeat feedback cue after a change in task rules is referred to as *repetition trial*. The remaining trials within a run of rule repetitions were not included in our analyses.

Mean response times (RTs) and error rates were calculated separately for switch trials, addendum switch trials, and repetition trials. RTs faster than 100 ms or slower than three standard deviations above the mean for each participant were excluded. Switch trials were only included when participants switched to one of the two equally likely rules in the high-uncertainty condition or to the more likely of two rules in the low-uncertainty condition, respectively. We decided to exclude switches to the less likely rule in the low-uncertainty condition to obtain a homogenous pool of switch trials on which participants considered the differential rule likelihoods. Note however, that switches to the less likely rule occurred only very rarely (i.e., in about 20% of the trials, see results) and that the reported results do not change qualitatively when these trials are included (i.e., significant effects remain significant and not significant effects remain not significant). Addendum switch trials were only included when they followed an included switch trial and when participants switched to the correct rule on the addendum switch trial. Repetition trials were included when they followed an included switch or addendum switch trial and when participants repeated sorting according to the correct rule on the repetition trial.

Error rates were calculated as the percentage of incorrect responses. For switch trials, only perseverative errors (i.e., repetitions of the previously correct, but now incorrect rule) were counted as errors (Lange, Seer, Müller et al., 2015). Efficient errors (i.e., switches to an incorrect rule) are a necessary element required to identify the correct task rule after a rule switch (Barceló, 1999; Barceló & Knight, 2002), and they were thus not considered to be incorrect responses. Addendum switch trials were only included for the analysis of error rates when they followed an efficient error on the switch trial. Repetition trials were included when they followed a switch or addendum switch trial.

We performed 3 × 2 × 2 × 2 repeated-measures ANOVAs involving the factors trial type (switch vs. addendum switch vs. repetition), rule uncertainty (high vs. low), likelihood (80% vs. 60%), and CTI (1200 ms vs. 300 ms) on participants' RTs and error rates. By this means, we aimed to examine whether the effects of rule uncertainty on switch- and addendum-switch-specific cWCST performance shown in our previous study (Lange, Seer, Müller et al., 2015) would replicate in this independent sample. In addition, we wanted to test whether the trial type × rule uncertainty interaction is affected by the degree of rule uncertainty in the low-uncertainty condition (i.e., the likelihood of the more likely rule) and/or the amount of available preparation time (i.e., the CTI). If rule-uncertainty effects are more pronounced when rule-uncertainty is especially low (i.e., when the likelihood of the more likely rule is higher), we would expect a three-way interaction between trial type, rule uncertainty, and likelihood. If rule-uncertainty effects are mediated by active preparation processes (which should be more effective at long CTIs), we would expect a three-way interaction between trial type, rule uncertainty, and CTI.

Statistical analyses were performed using SPSS 24.0 (IBM, Armonk, NY). We report Greenhouse-Geisser corrected degrees of freedom and *p*-values. The level of significance was set at $\alpha = .05$. As described above, we focused on the replication of the two-way interaction between rule uncertainty and trial type as well as on the three-way interactions that additionally involve the factors likelihood and CTI. In case of significant interactions, we decomposed them by analysing differences between means or pairs of means. These follow-up analyses were conducted to illustrate and explore the nature of any potential interactions. Their results were not corrected for multiple comparisons and we note that our study would not have sufficient statistical power to adequately control for the number of possible follow-up tests. All ANOVA results as well as the corresponding descriptive data can be found in the Supplementary Materials.

Results

Participants chose the more likely rule on 79% percent of the switch trials in the low-uncertainty condition. This percentage was larger in the high-likelihood condition (82%, *SD* = 13%) than in the low-likelihood condition (76%, *SD* = 15%), $F(1, 24) = 7.54$, $p = .011$, $\eta_p^2 = .24$.

The 3 (trial type) × 2 (rule uncertainty) × 2 (likelihood) × 2 (CTI) ANOVA on RT data revealed a significant effect of trial type, $F(1.63, 39.00) = 122.478$, $p < .001$, $\eta_p^2 = .84$, that was moderated by a significant trial type × rule uncertainty interaction, $F(1.25, 30.07) = 10.55$, $p = .002$, $\eta_p^2 = .31$. RTs on switch trials were 85 ms faster in the low-uncertainty condition as opposed to the high-uncertainty condition, $F(1, 24) = 6.94$, $p = .015$, $\eta_p^2 = .22$. In contrast, RTs on addendum switch trials were 86 ms faster in the high-uncertainty condition as opposed to the low-uncertainty condition, $F(1, 24) = 10.93$, $p = .003$, $\eta_p^2 = .31$. RTs on repetition trials did not vary significantly as a function of rule uncertainty, $F(1, 24) = 0.12$, $p = .731$, $\eta_p^2 = .01$. The interaction of trial type and rule certainty was not significantly modulated by likelihood, $F(1.46, 34.95) = 0.53$, $p = .538$, $\eta_p^2 = .02$, or CTI, $F(1.92, 46.17) = 1.57$, $p = .219$, $\eta_p^2 = .06$.

Error-rate analysis revealed a significant main effect of trial type, $F(1.89, 45.44) = 31.41$, $p < .001$, $\eta_p^2 = .57$, as well as a significant trial type × rule uncertainty interaction, $F(1.51, 36.18) = 5.19$, $p = .017$, $\eta_p^2 = .18$. Rule uncertainty neither affected the number of perseverative errors committed on the switch trial, $F(1, 24) = 1.52$, $p = .230$, $\eta_p^2 = .06$, nor repetition-trial accuracy, $F(1, 24) = 0.27$, $p = .612$, $\eta_p^2 = .01$. However, error rates on addendum switch trials were significantly lower in high-uncertainty (9%) as opposed to low-uncertainty conditions (13%), $F(1, 24) = 5.57$, $p = .027$, $\eta_p^2 = .19$. The interaction of trial type and rule certainty was not significantly modulated by likelihood, $F(1.30, 31.18) = 0.69$, $p = .448$, $\eta_p^2 = .03$, or CTI, $F(1.32, 31.69) = 0.96$, $p = .359$, $\eta_p^2 = .04$.

Note that CTI exerted substantial effects on both RTs and error rates, and that these effects were particularly pronounced on switch trials and addendum switch trials. Given our focus on rule-uncertainty effects (and their potential moderation by CTI), we will not describe these effects here but in the Supplementary Materials.

Discussion

The interactive effect of trial type and rule uncertainty found by Lange, Seer, Müller, and colleagues (2015) was replicated in Study 1 (see Figure 3). When rules were selected under reduced rule uncertainty, response latencies on the switch trial decreased, whereas RTs and error rates on the addendum switch trial increased. Larger reductions of rule uncertainty (i.e., making the more likely rule even more likely to be correct) did not result in a significant enhancement of these rule-uncertainty effects. Compared to the 60% likelihood condition, participants chose the more frequent rule more frequently in the 80% likelihood condition. However, this increased bias for one of the two possible rules on the switch trial did not lead to a further decrease in response latencies when switching rules, nor did it impair performance when a switch away from the more likely rule was required on the addendum switch trial. This lack of a moderating effect of rule likelihood on the trial type × rule uncertainty interaction may be due to our manipulation of rule likelihood not being strong enough to substantially modulate the bias towards the more frequent rule. Despite being significant, the difference between likelihood conditions in the preference for the more frequent rule was rather small (76% vs. 82%). Future replication studies using a wider range of likelihood conditions may allow examining whether participants' performance on the cWCST can be tuned to varying degrees of rule uncertainty. Relatedly, the size of our sample might have been too small to allow for a powerful test of rule-likelihood effects. Note that our sample size was determined to be large enough to detect the effects reported by Lange, Seer, Müller, and colleagues (2015). A possible moderation of these effects by rule likelihood (or any other factor) might be substantially smaller in magnitude and, hence, may have gone undetected in the present study. Alternatively, it is of course possible that cWCST performance is not sensitive to numeric differences in rule uncertainty. Having the information that one rule is more likely than the alternative rule (be it 60% or 80%) might be sufficient to induce a relatively invariable commitment to this rule, which is then harder to be overcome on the addendum switch trial.

Along similar lines, rule-uncertainty effects were unaffected by CTI length, which implies that our data fail to support a role of active preparation processes in the mediation of the effect of rule uncertainty on cWCST performance. However, the lack of evidence for a CTI effect on the interaction between rule uncertainty and trial type of course does not rule out the existence of such an effect. Again, the chosen CTI levels might not have been extreme enough to evoke detectable effects on the trial type × rule uncertainty interaction.

Finally, it has to be noted that neither the proportion of perseverative errors committed on switch trials nor repetition-trial performance was affected by our manipulation of rule uncertainty. This result is consistent with the data presented by Lange, Seer, Müller, and colleagues (2015, see Figure 3) and suggests that reducing the rule uncertainty that is typically associated with the WCST seems to have dissociable influences on different aspects of cWCST performance.

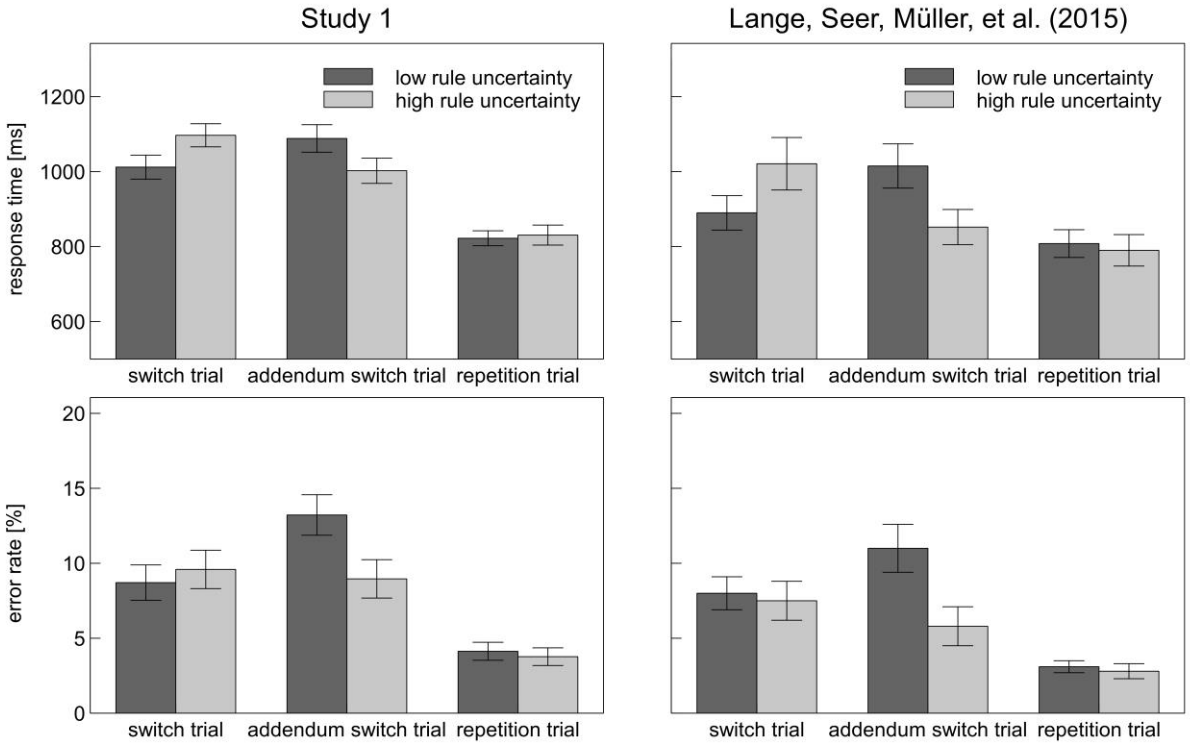

Figure 3. Performance data obtained in Study 1 (left). Performance data obtained in the Study reported by Lange, Seer, Müller, and colleagues (2015, right) is presented to facilitate the comparison of the replicated interaction between rule uncertainty and trial type. Response latencies (top) and error rates (bottom) are depicted as a function of trial type and rule uncertainty. Note that only perseverative errors have been considered for the calculation of error rates on the switch trial. Error bars represent standard errors of the mean.

Study 2

With Study 2, we set out to explore an additional boundary condition of the effects of rule uncertainty on cWCST performance. Both in Study 1 and in our previously published study (Lange, Seer, Müller et al., 2015), actual rule uncertainty and instructed rule uncertainty were always aligned. We instructed participants that, in the low-uncertainty condition, one rule would be more likely to be correct than the other, and actual rule likelihoods corresponded with this instruction. In Study 2, we kept actual rule likelihoods constant across high-uncertainty and low-uncertainty conditions, that is, when participants switched away from one rule, the two remaining rules were always equally likely to be correct. However, in one condition, we instructed participants (as in our previous studies) that one rule would be more likely to be correct. Observing a similar trial type × rule uncertainty interaction as in our previous studies in this condition would suggest that instructions are sufficient to produce rule-uncertainty effects on cWCST performance (i.e., that participants do not need to experience uneven rule uncertainties themselves).

Moreover, we included a control condition where all rule changes occurred under high rule uncertainty. In this condition, participants were told that when switching away from one rule, the remaining two rules were always equally likely to be correct, and actual rule likelihoods corresponded with this instruction. Similar rule likelihoods are associated with (early stages of) the WCST where, upon a rule change, participants do not have any information as to which of the remaining rules might be more likely to be correct. By contrasting this control condition with our experimental condition with instructed differences in rule likelihoods, we were able to analyse which rule transitions are affected by the reduction of rule uncertainty. In our previous studies, we repeatedly showed that our manipulation of rule uncertainty led to RT and accuracy differences between high-uncertainty and low-uncertainty conditions. However, it was not possible to decide whether these differences result from changes in the high-uncertainty condition or from changes in the low-uncertainty condition. To illustrate, switching rules on the switch trials in Study 1 was about 85 ms faster in the low-uncertainty condition than in the high-uncertainty condition. This difference can be the result of accelerated responses when switching to the more likely rule or of slowed responses when switching away from this rule to one of two equally likely rules (or both). Comparing performance measures obtained from high-uncertainty and low-uncertainty conditions with a control condition where all rules are equally likely to be correct allows dissociating the contributions of these two alternative sources of rule-uncertainty effects on cWCST performance.

Methods

Participants. Twenty-five university students (15 female; 10 male; mean age = 23.41 years, *SD* = 2.64 years) with normal or corrected-to-normal vision participated for course credit. The reported study has been approved by the Ethics Committee of Hannover Medical School and was carried out in accordance with the approved protocol. Informed consent was obtained from all participants. The same sample size rationale was applied as in Study 1.

Task, design, and procedure. We used the same task and apparatus as in Study 1. As we intended to change as few experimental details as possible between Study 1 and Study 2, the manipulation of CTI length between blocks was also repeated in Study 2. Repeating this manipulation also partially addresses the possibility that the lack of a significant CTI effect in Study 1 was a false negative. We used the same CTI, RCI, RTI, and cue-presentation-time parameters as in Study 1.

In contrast to Study 1, we manipulated (between blocks) the instruction about rule likelihoods given to participants. In the experimental condition, participants sorted cards under the same instruction as in the 60% likelihood condition of Study 1. They were told that one of the three rules would be more frequent than the others, implying that this rule would have an increased likelihood (60%) of being correct after a switch away from one of the other two rules (low-uncertainty condition). After a switch away from this more likely rule, the remaining two rules were instructed to be equally likely to be correct (high-uncertainty condition). In the control condition, participants were instructed that all rules would be equally frequent, implying that after a switch away from one rule, the two remaining rules would be equally likely to be correct. Actual rule likelihoods did not differ between the experimental and the control condition: the two possible rules after a switch were always equally likely to be correct.

Participants completed four blocks of cWCST trials, each consisting of 72 runs. The two blocks corresponding to each of the instruction conditions were presented in direct succession with the order of instruction conditions being counterbalanced across participants. The order of CTI blocks within the grouped instruction blocks was counterbalanced as well.

Data analysis. If participants' choice behaviour on the switch trial is affected by the instruction of differential rule likelihoods, we would expect more choices of the rule that is instructed to be more likely to be correct in the experimental condition. In the control condition, the same rule should not be systematically preferred. For the purpose of our analyses, we declared this rule to be the more likely rule, although it is a) not actually more likely than the alternative rule and b) only instructed to be more likely than the alternative rule in the experimental but not in the control condition. As a consequence, we are referring to, for example, low-uncertainty conditions in the control condition, although the control condition is characterized by the absence of rule changes under reduced uncertainty. This labelling merely reflects that we are referring to control trials that are identical to the matched trials in the experimental condition in every respect except the instruction of differential rule likelihoods. Hence, a switch trial in the low-uncertainty condition of the control condition is a trial where participants can choose to switch to the rule that is instructed to be more likely to be correct in the corresponding experimental condition (see Figure 4).

RTs and error rates were subjected to 3 × 2 × 2 × 2 repeated-measures ANOVAs involving the factors trial type (switch vs. addendum switch vs. repetition), rule uncertainty (high vs. low), instruction (experimental vs. control), and CTI (1200 ms vs. 300 ms). If the instruction of differential rule uncertainties is sufficient to evoke the rule-uncertainty effects observed in Study 1, we would expect a trial type × rule uncertainty × instruction interaction with significantly larger uncertainty effects in the experimental as opposed to the control condition. In addition, decomposing this potential interaction should reveal whether rule-uncertainty effects are due to altered performance following low-uncertainty switches and/or altered performance following high-uncertainty switches.

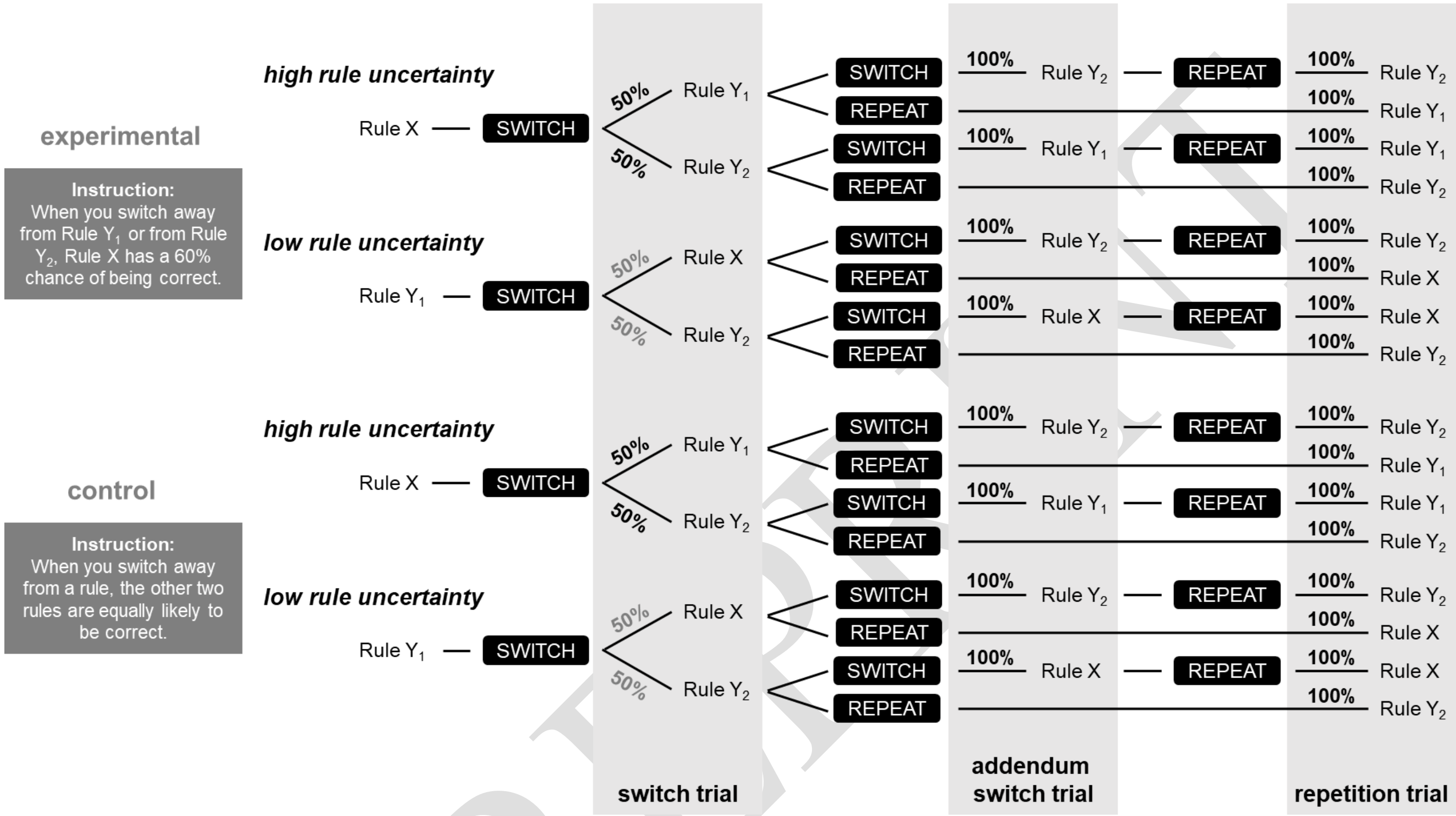

Figure 4. Experimental design of Study 2. The factors trial type (switch, addendum switch, repetition) and rule uncertainty (high, low) vary within a block while the factor instruction (experimental, control) is manipulated between blocks. Percentages denote conditional rule probabilities. Note that rule uncertainty is only instructed to differ between high- and low-uncertainty conditions. In the control condition, no such alleged difference in rule uncertainty is induced by the instruction. The differentiation between high and low uncertainty in the control condition merely reflects that the corresponding trials matched the trials in the experimental condition in every respect except the instruction of differential rule likelihoods.

Results

The mere instruction of differential rule likelihoods affected participants' choice behaviour on the switch trial. In the experimental condition, participants chose the rule that was instructed to be more likely to be correct on 76 % (*SD* = 14%) of the switch trials in the low-uncertainty condition. In the control condition, the same rule (i.e., the rule that was instructed to be more likely to be correct in the experimental condition) was not chosen disproportionally often (i.e., on 52 %, *SD* = 12%, of the switch trials in the low-uncertainty condition).

Along the lines of Study 1, a 3 (trial type) × 2 (rule uncertainty) × 2 (instruction) × 2 (CTI) ANOVA revealed rule-uncertainty effects on response latency on switch and addendum switch trials: The significant main effect of trial type, $F(1.45, 34.76) = 25.98$, $p < .001$, $\eta_p^2 = .52$, was qualified by a significant trial type × rule uncertainty interaction, $F(1.11, 26.66) = 11.43$, $p = .002$, $\eta_p^2 = .32$. As in Study 1, this interaction was not further modulated by CTI, $F(1.38, 33.22) = 0.02$, $p = .940$, $\eta_p^2 = .00$. However, there was a significant trial type × rule uncertainty × instruction interaction, $F(1.16, 27.86) = 5.18$, $p = .026$, $\eta_p^2 = .18$, indicating that the trial type × rule uncertainty interaction was more pronounced in the experimental condition, $\eta_p^2 = .30$, than in the control condition, $\eta_p^2 = .14$ (Figure 5). Note that the effect size of the trial type × rule uncertainty interaction in the experimental condition was very similar to the corresponding effect size found in Study 1 (i.e., $\eta_p^2 = .31$).

Instruction modulated the effect of rule uncertainty on switch-trial RT, $F(1, 24) = 5.27$, $p = .031$, $\eta_p^2 = .18$. Switches in the low-uncertainty condition did not differ significantly in response latency between the experimental (*M* = 1312 ms) and the control condition (*M* = 1304 ms), $F(1, 24) = 0.02$, $p = .900$, $\eta_p^2 = .00$. In contrast, switches in the high-uncertainty condition tended to be slower in the experimental condition (*M* = 1522 ms) as compared to the control condition (*M* = 1345 ms), $F(1, 24) = 3.02$, $p = .095$, $\eta_p^2 = .11$. Instruction also modulated the effect of rule uncertainty on addendum-switch-trial RT, $F(1, 24) = 4.37$, $p =$

.047, η_p^2 = .15. Addendum switches in the low-uncertainty condition tended to be slower in the experimental condition (*M* = 1366 ms) than in the control condition (*M* = 1138 ms), *F*(1, 24) = 3.43, *p* = .076, η_p^2 = .13. RTs on addendum switch trials in the high-uncertainty condition did not differ significantly between the experimental condition (*M* = 1061 ms) and the control condition (*M* = 1029 ms), *F*(1, 24) = 0.25, *p* = .619, η_p^2 = .01. With regard to RT on repetition trials, the main effect of rule uncertainty, *F*(1, 24) = 0.19, *p* = .666, η_p^2 = .01, as well as the rule uncertainty × instruction interaction, *F*(1, 24) = 0.81, *p* = .378, η_p^2 = .03, were not significant.

A 3 (trial type) × 2 (rule uncertainty) × 2 (instruction) × 2 (CTI) ANOVA on error-rate data revealed a significant main effect of trial type, *F*(1.28, 30.76) = 21.84, $p < .001$, η_p^2 = .48. The trial type × rule uncertainty interaction, *F*(1.66, 39.73) = 2.14, *p* = .139, η_p^2 = .08, as well as the trial type × rule uncertainty × instruction interaction, *F*(1.53, 36.78) = 0.68, *p* = .475, η_p^2 = .03, and the trial type × rule uncertainty × CTI interaction, *F*(1.63, 39.21) = 0.11, *p* = .858, η_p^2 = .01, did not reach significance.

As in Study 1, we found main and interaction effects that involved the factor CTI, but not the factor rule uncertainty. These effects are described in the Supplementary Materials.

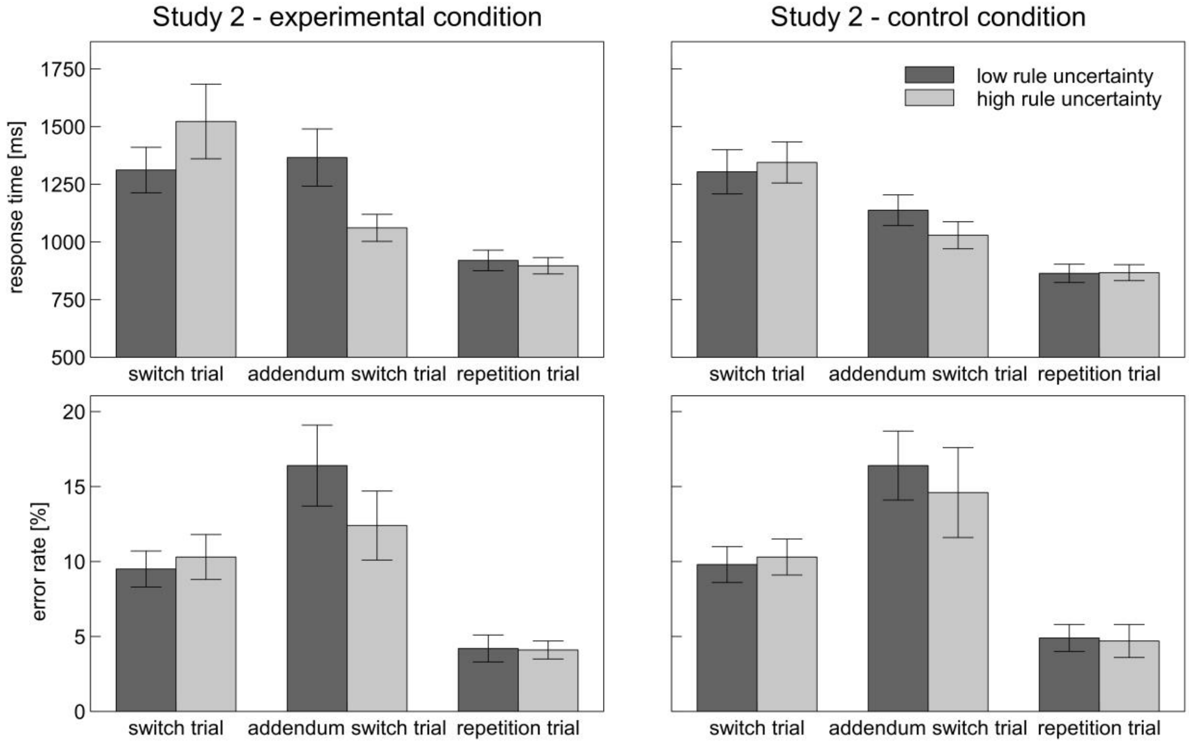

Figure 5. Performance data obtained in Study 2. Response latencies (top) and error rates (bottom) are depicted as a function of trial type, rule uncertainty, and condition. In the experimental condition (left) participants were instructed that one rule would be more frequent than the other two (i.e., more likely to be correct when participants are cued to switch away from one of the other rules). In the control condition (right), participants were instructed that all rules are equally frequent. Note that only perseverative errors have been considered for the calculation of error rates on the switch trial. Error bars represent standard errors of the mean.

Discussion

The significant three-way interaction of trial type, rule uncertainty, and instruction suggests that instructions are sufficient to induce rule-uncertainty effects on cWCST performance. In comparison to the high-uncertainty condition, we observed the familiar pattern of decreased switch-trial RT and increased addendum-switch-trial RT following low-uncertainty switches in the experimental condition, although actual rule likelihoods did not favour one of the rules in these situations.

The effect of rule uncertainty on response latencies on the switch trial seems to be due to a prolongation of RTs in the high-uncertainty condition: When switching away from the more likely rule, switching to one of two equally likely rules tended to be slower than switching to one of two equally likely rules under standard WCST rule likelihoods. In contrast, the effect of rule-uncertainty on addendum-switch-trial RT appears to result from slowed responses in the low-uncertainty condition: The instruction of unequal rule likelihoods in the experimental condition decelerated low-uncertainty addendum switches as compared to the corresponding trials in the control condition. Note that these explanations can only be generalized to the rule-uncertainty effects in Study 1 and the study by Lange, Seer, Müller, and colleagues (2015) to the extent to which the uncertainty effects in those studies were driven by instructions. With Study 2, we have shown that instructions contribute to rule-uncertainty effects on cWCST performance, but this does not imply that actual rule likelihoods did not contribute to the rule-uncertainty effect in, for example Study 1. It is noteworthy that the interactive effect of rule uncertainty and trial type on cWCST error rates was larger in Study 1 (η_p^2 = .18) than in Study 2 (overall: η_p^2 = .08; experimental condition only: η_p^2 = .10). In contrast, the rule uncertainty × trial type interaction on RTs found in Study 1 (where both actual and instructed likelihoods favoured a particular rule) was not stronger than the corresponding interaction in the experimental condition of Study 2 (where only instructed likelihoods favoured one of the cWCST rules).

An unexpected finding is the significantly reduced but still substantial trial type × rule uncertainty interaction on RTs in the control condition (where all rules were instructed to be equally likely to be correct). We speculated that this effect might be due to carry-over effects from the experimental condition in our within-subject design. However, adding the starting condition (experimental vs. control) as a between-subject factor to our ANOVAs did not result in significant starting condition × instruction × rule uncertainty × trial type interactions (RT: $F(1.17, 24) = 1.15$, $p = .303$, $\eta_p^2 = .05$; error rates: $F(1.53, 24) = 0.08$, $p = .881$, $\eta_p^2 = .00$). Similarly, the starting condition × rule uncertainty × trial type interactions were not significant (RT: $F(1.12, 24) = 1.77$, $p = .196$, $\eta_p^2 = .07$; error rates: $F(1.61, 24) = 0.79$, $p = .438$, $\eta_p^2 = .03$). Hence, our data do not support the contribution of carry-over effects to rule-uncertainty effects in the control condition. This result indicates that rule-uncertainty effects in the control condition were either driven by another factor or that statistical power was not sufficient to detect the contribution of carry-over effects in higher-order interactions.

General Discussion

Across multiple studies and a variety of task parameters, rule uncertainty has been observed to exert significant effects on the efficiency of rule switches on a computerized version of the WCST. Reducing the uncertainty about rules associated with the standard version of the WCST consistently impaired some aspects of cWCST performance while leaving other measures (e.g., the number of perseverative errors) unaffected. In the remainder of this article, we discuss the implications of these findings for the understanding of cognitive flexibility and in particular for the relationship between WCST data and data obtained from the experimental task-switching paradigm.

The perhaps most salient and robust finding observed across our studies was the interaction of trial type and rule uncertainty in determining participants' response latencies. Uncertainty reductions resulted in prolonged RTs when a more likely rule turned out to be incorrect and had to be changed on the addendum switch trial. These rule-uncertainty effects on addendum-switch-trial RT can be accounted for by applying the cognitive branching model (Koechlin & Hyafil, 2007) to the explanation of cWCST performance (Lange, Seer, Müller et al., 2015). When two (c)WCST rules are equally likely to be correct, individuals might choose one task rule for execution while the alternative task rule is maintained in a pre-active state. When the chosen rule then turns out to be incorrect (i.e., when an addendum switch is required), switching to the alternative rule is accelerated due to its pre-activation. In contrast, as soon as individuals are given the opportunity to commit to one task rule (due to decreased rule uncertainty), switching away from this rule appears to be more effortful.

Alternatively, it is possible that performance decrements on addendum-switch trials under reduced rule uncertainty reflect a surprise response or a recovery from a violation of expectation. Our manipulation of rule uncertainty necessitates that addendum switch trials are less likely to occur in high-uncertainty conditions than in low-uncertainty conditions. In the low-uncertainty condition, participants have more reason to expect the rule chosen on the switch trial to be correct. The encounter of an additional switch feedback violates this expectation and performance deficits might be attributable to the associated surprise or confusion. However, this alternative explanation predicts that addendum-switch performance would be more impaired when the global probability of encountering an addendum switch trial decreases even further. We did not observe a corresponding effect of manipulating the likelihood of the most frequent rule (and, as a corollary, the likelihood of addendum switch trials) in Study 1. In addition, this explanation cannot account for the rule-uncertainty effect on switch-trial RT, which is likely driven by the increased difficulty to disengage from a task rule that has been selected under low uncertainty. Study 2 revealed that reducing the uncertainty involved in some rule changes increases response latencies for the remaining rule changes (i.e., rule changes that still occur under high rule uncertainty). In contrast to high-uncertainty rule changes under standard WCST conditions, these high-uncertainty rule changes required switching away from the more frequent rule (i.e., a rule that has been selected under low uncertainty). Hence, it appears that the speed of switching cognitive rules is increased by the high level of rule uncertainty that is characteristic to the WCST and that discourages full commitment to single task rules.

Effects of reduced rule uncertainty can be observed both when participants are given a comparatively strong reason (one of the two rules is correct in 80% of the cases) and when they are given a comparatively weak reason (one of the two rules is correct in 60% of the cases) to commit to one of the task rules (Study 1). In addition, it is even sufficient to instruct participants about subtle differences in rule likelihoods to impede performance on switch and addendum switch trials (Study 2), and these performance decrements do not seem to be amendable by giving participants more preparation time to overcome the commitment to the more likely task rule (Study 1 & 2). The contribution of rule uncertainty to response latency on the cWCST thus seems to be rather robust and at least partially driven by participants' top-down expectancies about differential rule likelihoods.

The possibility to study uncertainty effects on cognitive flexibility underlines the potential value of the cWCST for experimental researchers using task-switching paradigms. Manipulations of the uncertainty about an upcoming task transition have repeatedly been used to examine preparation effects on task-switching performance (Dreisbach & Haider, 2006; Dreisbach, Haider, & Kluwe, 2002; Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004; Ruthruff, Remington, & Johnston, 2001; Wendt, Luna-Rodriguez, Reisenauer, Jacobsen, & Dreisbach, 2012). For example, Wendt and colleagues (2012) used advance cues that informed participants about the task they should apply on the upcoming trial. However, on a subset of trials, the advance cue was overruled by a second cue that signalled that a different task should be applied instead. This invalid cuing procedure bears a striking resemblance to the cWCST paradigm presented here: Both on invalidly cued task-switching trials and on addendum-switch trials in the cWCST, participants have to revise their belief about the currently valid task rule. However, in contrast to studies using invalid cues, participants completing the cWCST do not only prepare a rule for execution, but they actually execute this rule on the switch trial. In other words, the processes of initial rule selection and rule revision are temporally dissociated in our cWCST paradigm, which illustrates its potential to complement existing approaches to study uncertainty effects on task-switching processes.

While the rule-uncertainty effects on response latencies discussed above are informative with regard to the interplay of uncertainty and cognitive flexibility, they may be less relevant for the interpretation of WCST data obtained in neuropsychological contexts. The WCST does not involve a time component and common WCST measures (Heaton et al., 1993) exclusively reflect response accuracy. Hence, rule-uncertainty effects on cWCST response latencies do not imply that WCST performance scores are affected by rule uncertainty (i.e., by a factor that differs between the WCST and task-switching paradigms).

From a neuropsychological perspective, systematic rule-uncertainty effects on error measures pose a more serious problem for the comparison of WCST and task-switching data. Our data indicate that participant's accuracy on addendum switch trials decreases when participants have to switch away from a rule that has been selected under reduced rule uncertainty. A large number of errors on addendum switch trials are characterized by a switch back to a rule that participants should have been able to exclude based on the performance feedback received on previous trials. We have previously referred to these errors as integration errors (Lange, Kröger et al., 2016; Lange, Seer, Dengler, Dressler, & Kopp, 2016). Integration errors likely reflect failures to infer the correct new rule and they have been shown to be affected by a different manipulation related to rule uncertainty (i.e., increasing the number of cWCST rules; Lange, Kröger et al., 2016). On standard versions of the WCST, integration errors contribute to the number of non-perseverative errors and also affect the number of completed categories. Our findings thus indicate that rule uncertainty complicates relating these WCST performance measures to measures of task-switching performance. A clinical group showing a reduced number of categories and an increased number of non-perseverative errors can have intact task-switching abilities because these performance deficits can also be explained by the demands for uncertainty processing unique to the WCST. Children with Gilles de la Tourette syndrome (GTS) might constitute an example for such a group. Early neuropsychological studies (Bornstein, 1990; Yeates & Bornstein, 1994, 1996;

see Lange, Seer, Müller-Vahl, & Kopp, 2017, for a meta-analysis) have shown that children with GTS complete fewer WCST categories (with mean *T* scores ranging from 42 to 44), whereas the number of perseverative errors was relatively normal (with mean *T* scores ranging from 48 to 50). In contrast, young people with GTS have repeatedly been reported to outperform age-matched controls in a task-switching paradigm (Jackson, Mueller, Hambleton, & Hollis, 2007; Jung, Jackson, Nam, Hollis, & Jackson, 2015; Mueller, Jackson, Dhalla, Datsopoulos, & Hollis, 2006). The WCST deficits observed in children with GTS are thus likely to relate to task demands (e.g., for uncertainty processing) that are not shared with experimental task-switching paradigms.

In this context, it is important to note that the number of perseverative errors committed on switch trials of the cWCST was not significantly affected by rule uncertainty in any of the studies reported here or in our previous study (with effect sizes ranging from $r = -.04$ to $r = .12$, mean $r = .05$, 95%-CI [-.19 – .28]). Similarly, the number of perseverative errors did not vary depending on the number of viable cWCST rules in another one of our previous studies (Lange, Kröger et al., 2016). As a consequence, comparisons between perseverative tendencies on the WCST and task-switching performance (as measured by, e.g., RT switch cost) do not seem to be complicated by rule-uncertainty differences between the two types of measures. This idea receives further support from correlations between task-switching performance and the number of perseverative WCST errors (Miyake et al., 2000) as well as from the presence of both perseverative WCST deficits and task-switching impairments in patients with Parkinson's disease (e.g., Cools et al., 2001; Crescentini, Mondolo, Biasutti, & Shallice, 2012; Kudlicka et al., 2011), obsessive-compulsive disorder (e.g., Gu et al., 2008; Shin et al., 2014) and frontal lobe lesions (e.g., Demakis, 2003; Mayr, Diederichsen, Ivry, & Keele, 2006).

Based on these findings, we propose that the problem of task impurity that has frequently been held against the validity of the WCST as a cognitive flexibility task can partially be solved by a differentiated analysis of WCST performance. Some aspects of WCST performance (such as the number of completed categories) are likely to be affected by task features (e.g., rule uncertainty) that are unique to the WCST and that are not shared with experimental task-switching paradigms. Other measures (such as the number or proportion of perseverative errors) might reflect cognitive processes that are very similar to the processes required in experimental task-switching paradigms. The purity of these measures should further increase when narrower operational definitions are applied. In our studies, we only considered perseverative errors that occurred on the first trial after participants had been informed about a change in task rules. By restricting the analysis to these situations, it is possible to eliminate the confounding of different types of perseverative errors that have been shown to be only moderately related to each other (Godinez, Friedman, Rhee, Miyake, & Hewitt, 2012). In combination with a refined analysis of non-perseverative WCST errors (Barceló, 1999; Barceló & Knight, 2002; Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000; Nyhus & Barceló, 2009; Lange, Kröger et al., 2016), narrower definitions of perseverative WCST errors may further facilitate the mapping of WCST performance scores to distinct cognitive processes. As a corollary, such a differentiated analysis of WCST errors may further improve the translatability between the WCST and more specific experimental task-switching paradigms.

Limitations

It is important to note that our results obtained from the cWCST can be transferred to standard versions of the WCST only to the degree to which these paradigms involve similar cognitive processes. In contrast to standard WCST versions, participants completing the cWCST in our studies were instructed about the three possible rules, informed that the valid task rule would change from time to time, and allowed to practice the task. These procedural changes allowed focusing on the WCST feature most relevant for our current set of analyses (i.e., rule uncertainty). We do not think that these changes undermine the validity of the cWCST because a) comparable changes have been made in a number of previous studies on the factors contributing to WCST performance (Barceló, 1999; 2003; Barceló et al., 2000; Lange, Kröger et al. 2016) and b) previous data show a strong correlation between cWCST performance and performance on a manual version of the WCST (Lange, Seer, Loens et al., 2016).

The demographics of the participants serving in our studies constitute a second factor limiting the generalizability of our results. Our decision to exclusively include university students was mainly motivated by practical reasons. For example, even our young participants required more than 90 minutes to complete the experimental conditions involved in Study 2. From an earlier study in an age-diverse sample (M_{age} = 50 years, SD_{age} = 17 years) we know that RTs on cWCST trials increase drastically in older individuals (e.g., switch-trial RT was more than twice as long as in the present studies; Lange, Kröger et al., 2016). Therefore, we did not think that it was feasible to conduct experiments at this level of elaboration in a sample of older individuals. Although we do not see a theoretical reason to assume that the observed rule-uncertainty effects should be restricted to the young population, a focused replication of our key finding in a sample of older participants would certainly be a sensible next step in studying the interplay of rule uncertainty and cognitive flexibility on the WCST.

Conclusion

Rule uncertainty drives the complexity differences between the WCST and experimental task-switching paradigms. However, our findings illustrate that rule uncertainty does not necessarily undermine the validity of the WCST as a measure of cognitive flexibility. While gross measures of WCST performance may reflect the confounding of cognitive flexibility and uncertainty processing, a fine-grained WCST analysis has the potential to differentiate indicators of dissociable cognitive processes (e.g., perseverative errors vs. integration errors on addendum switch trials). By this means, it is possible to integrate WCST results and findings obtained from less complex tasks of cognitive flexibility.

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