Assessing Strategic Flexibility: Strategy-Shifting as a Mechanism of Cognitive Reserve

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Abstract

This series of experiments explores the potential role of strategic flexibility in cognitive aging, and whether this construct can serve as a mechanism for cognitive reserve. A strategic flexibility task was designed utilizing matrix reasoning stimuli that each required one of two specific solution strategies: logico-analytic and visuospatial. It was formatted as a task-switching paradigm, assessing the ability to switch between solution strategies. Study 1 demonstrated the presence of switch-costs on this task using commonly measured metrics, as well on an alternate measure of task performance that combines reaction time and accuracy. Age-related switch-costs were noted, similar to those reported in set switching tasks using simpler items. Study 2 included assessment of CR proxies and introduced a redesigned version of this task, matching it more closely to existing paradigms of task-switching. It again found switch-costs that increased with aging. In addition, a relationship between switch-costs and CR proxies was noted, suggesting a relationship between strategic flexibility and CR. Study 3 utilized participants who had been studied extensively with neuropsychological assessments and structural neuroimaging. It aimed to investigate the associations between these data and measures of strategic flexibility. Results again indicated that age negatively affected strategic flexibility, but that individuals with higher CR as measured with standard proxies performed better. We then tested whether strategic flexibility moderated the relationship between cortical thickness and measures of cognitive performance. The strategic flexibility measure accounted for additional variance in cognitive performance over that explained by cortical thickness, suggesting that it may contribute to CR. Overall, the results are consistent with the idea that strategic flexibility might be one cognitive process that underlies cognitive reserve.

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Keywords: cognitive strategies, cognitive aging, task-switching, cognitive flexibility, cognitive reserve

Public Significance Statement

Healthy older adults were less capable of switching between distinct cognitive strategies while performing a reasoning task. Higher estimated Cognitive Reserve was found to be associated with greater switching ability, or strategic flexibility. Such strategic flexibility was found to explain cognitive performance in several domains even after taking into account brain measures, suggesting that enhancing flexibility of cognitive strategies may provide protection against cognitive decline.

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Assessing Strategic Flexibility: Strategy-Shifting as a Mechanism of Cognitive Reserve

Cognitive reserve (CR) can be defined as “a property of the brain that allows for cognitive performance that is better than expected given the degree of life-course related brain changes and brain injury or disease” where “property of the brain refers to multiple potential mechanisms including molecular, cellular and network levels” (<https://reserveandresilience.com/>). Thus life exposures, brain networks or cognitive processes associated with CR would be expected to either moderate the impact of age- or disease-related brain changes on cognitive function, or to account for unique variance above that predicted by brain measures. Most studies of CR have been either epidemiologic, looking at the wide-scale effects of lifestyle such as education, IQ or occupational attainment on rates of cognitive aging and disease prevalence, or have utilized neuroimaging to examine how differential utilization of imaged brain processes might allow for better performance in the presence of brain changes (see D. Barulli & Stern, 2013 for a review). The present series of studies attempts to understand CR as a function of cognitive operations, specifically differential flexibility in the utilization of cognitive strategies.

It has been suggested that the potential neurofunctional mechanisms underlying CR can be classified as either neural reserve or neural compensation (Stern, 2009). Neural reserve involves individual differences in cognitive networks used by unimpaired individuals and might consist of individual differences in the efficiency, capacity, and flexibility of a given set of task-related neural networks. Efficiency is commonly thought to mean the ability of that network to accomplish a given function with some limited amount of activation, while capacity refers generally to the ability of that network to activate to some threshold at which the function

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attempted can be achieved. Flexibility can relate to the ability to use alternate solution strategies, or to choose the best strategy.

While the study of CR using these hypothetical mechanisms and the tools provided by neuroimaging is valuable, some have pointed out that terms like efficiency and capacity are often too amorphous to always be truly explanatory (Poldrack, 2015). Efficiency and capacity may simply be placeholders for several much more detailed mechanistic explanations, including: a) an entirely different set of cognitive processes being performed, b) a different neural computation being performed to complete the same task, or c) fewer/more metabolic resources being demanded to perform the same neural computation for the same duration and at the same intensity. Neural compensation is rooted in a plethora of neuroimaging studies investigating the active recruitment of secondary brain networks to perform some cognitive task when the primary network has become impaired or overwhelmed (Li, Moore, Tyner, & Hu, 2009; Reuter-Lorenz & Cappell, 2008). However, some research hints that alternative patterns of fMRI-related network activation may not necessarily reflect compensatory activity at all. Sanfratello et al. (2014) argued that one likely source of group-wide variation in activation patterns is alternative strategy use among the elders, whose brains may have been afflicted by age-related neurological deterioration, as well as altered by experience-dependent shifts in cognitive strategy or style. Similarly, Kherif (2009) found that a subset of participants engaged in an alternate reading strategy that activates non-typical brain areas, but that these activation patterns are often washed out in group averaging. Accordingly, individual differences as well as age differences in strategic approaches must be taken into account for accurate generalization of neuroimaging findings

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(Sanfratello et al., 2014). Here we focus on flexibility of solution strategy as a possible cognitive mechanism for CR, using a task design that tightly constrains the strategies that are employed.

Cognitive Strategies

Many studies across a variety of domains have observed differences in cognitive strategy between young and old groups (see Lemaire, 2010 for a review). Dunlosky & Herzog (2001) for instance showed that while both young and old adults had access to the same total range of strategies for solving Paired Associates-style problems, the relative distribution of those strategies differed across groups. Other research suggests that older adults spontaneously access a fewer number and diversity of strategies. Duverne and Lemaire (2004) showed that in a study of arithmetical inequality verification, younger adults relied broadly on two classes of strategies – an exhaustive and approximate verification strategy – whereas older adults relied predominantly only on the exhaustive strategy. Even among tasks with arguably greater ecological validity, such as consumer decision-making tasks, age-related differences in strategy use have been observed. Payne et al. (1988) showed that when searching information about potential cars to purchase, young and older adults were likely to use different strategies.

The presence and magnitude of age effects can also depend strongly on the strategy and task utilized, with some strategies leading to equal performance in young and old groups. Cohen & Faulkner (1983a) used a sentence–picture verification task to show that a “linguistic” strategy (relying on the verbal description of the picture) yielded age differences in performance while a “pictorial” strategy did not. Others have had similar observations (Gandini, Lemaire, & Dufau, 2008; Patterson & Hertzog, 2010; Schunn, Lovett, & Reder, 2001; Schunn & Reder, 2001).

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Strategic adaptivity, or the adjustment of strategy in order to best fit task-relevant parameters and maximize performance, has been shown in task domains including arithmetic, reasoning, and serial recall (Lemaire, 2010). In several studies utilizing a computational estimation paradigm requiring subjects to solve a series of two-digit multiplication problems with one of two strategies (rounding both numbers either up or down prior to multiplying), Lemaire and his colleagues demonstrated that higher-order properties of cognitive strategies like strategy adaptivity are themselves subject to age effects. Strategy repertoire (the quantity of strategies known to the individual) has been shown as diminished among older adults relative to young (Lemaire, 2010); strategy distribution (the frequency at which each particular strategy is used) is often found to be lower among older individuals (Cohen & Faulkner, 1983a, 1983b; Gandini, Lemaire, & Dufau, 2008; Hartley & Anderson, 1983); strategy execution (the speed and accuracy at which a particular strategy is employed) is diminished in older groups (Siegler & Lemaire, 1997); and strategy selection (the cognitive processes affecting the choice of a particular strategy for a particular cognitive demand) has been demonstrated to be impaired in both healthy aging (Lemaire, Arnaud, & Lecacheur, 2004) and in subjects with pathological burden such as Alzheimer's disease (Lemaire & Leclère, 2014). Older adults also seem less capable of switching between strategies; i.e., the use of a particular strategy induces strategy switch-costs (in the form of longer RTs) on subsequent trials when another strategy would be more optimal (Ardiale, Hodzik, & Lemaire, 2012; Lemaire & Lecacheur, 2010), and this effect is even seen within the same item (Ardiale & Lemaire, 2012).

It is also possible that strategic flexibility may be one process underlying CR. In a previous study of cognitive strategies (D. J. Barulli, Rakitin, Lemaire, & Stern, 2013a), we found

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that IQ, a proxy for CR, moderated the effect of age on performance of a computational estimation paradigm: older adults chose the ‘best’ strategy (i.e., the strategy resulting in a product mathematically closer to the actual product) significantly less often than younger adults, but those with higher IQ exhibited performance more akin to those in the young group. This observation motivated a deeper inquiry into the nature of the coupling between cognitive strategy use and CR. Here we explore whether flexibility of cognitive strategies may represent one of the potential mechanisms through which CR moderates the effects of age-related brain changes on cognitive function. Some work has already been conducted along these lines in the realm of mnemonic strategies, with one study showing that mnemonic-strategy use moderates the effects of HIV-related dementia on verbal working memory (Woods et al., 2010), and such strategy use is associated with proxies for CR such as verbal intelligence and socioeconomic status.

The studies described here investigate the possibility that flexibility of solution strategy can be captured via a novel task assessing the ability to switch between cognitive strategies, and that differential flexibility is associated with differential CR. To do so, we developed an adaptation of a classic fluid reasoning test, set within the context of a task-switching paradigm. We selected matrix reasoning, often characterized by tasks such as Raven’s Progressive Matrices (RPM) test (Raven & others, 2003), as the foundation for the strategy task.

Despite its wide use in psychometrics, whether the RPM is best represented by a single underlying cognitive component or multiple such components was a matter of extensive research. Hunt (1974) suggested that two general problem-solving algorithms could be applied to the majority of RPM problems: first, a visual strategy (relying on perceptual reasoning, continuing perceptual patterns such as lines, and superimposition of elements onto one another); and second

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an analytic strategy that applies logical operations to features of the problem. This classification of RPM problems was later refined by various researchers: Kirby & Lawson (1983) suggested that two broad strategies could be employed in this task: gestalt strategies utilizing visuospatial operations, and analytic strategies utilizing logical and sequential operations. Carpenter, Just, & Shell (1990) later argued that the vast majority of RPM problems could be solved using just five abstract rules, some of which may be categorized as primarily analytical in nature and some as primarily visuospatial. Based partially on this and partially on the work of Hunt, DeShon, Chan & Weissbein (1995) suggested that all RPM problems were either of the visuospatial reasoning type, or of the analytical reasoning type. Furthermore, they identified two distinct sets of rules corresponding to the two strategies (e.g. object addition/subtraction for visuospatial problems, or quantitative pairwise progression for analytical problems). Here we made use of sets of matrix items whose solution relies on one of these two strategies.

Typically, set-switching tasks use simple classification tasks such odd/even, vowel/consonant, upper case/lower case. Then performance on blocks consisting of a single type of task are contrasted to blocks wherein participants alternate between two types of tasks. Here, we replaced these simpler tasks with matrix reasoning problems. We assembled two sets of simple matrix reasoning problems, with one requiring a visuospatial strategy and the other a logical-analytic strategy based on the taxonomies outlined above. We then developed a set-switching task using these problems as trials within either pure (only one type of strategy required) or mixed (both types of strategies required) blocks. We posited that the ability to switch between these two strategies could be considered an instantiation of flexibility of problem-

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solving. Further, we tested whether this flexibility was related to commonly used proxies of CR and whether flexibility itself acted like CR.

We report three experiments that examined the ability of healthy younger and older participants to flexibly switch their cognitive strategy and investigate how this measure of flexibility of solution strategy may be related to cognitive reserve. The first study describes the development and piloting of the initial version of the task. Our hypothesis was that older adults would display worse performance at higher-order strategy-shifting than younger adults (i.e., higher reaction times and lower accuracy), and that this shifting would result in comparable switch-costs to those seen in more typical task-switching tests. The second experiment used a revised version of the task with tighter controls on possible confounding variables, and included questionnaires which allowed us to estimate the CR of the participants. Here we hypothesized that i) older adults would again exhibit poorer switch-costs relative to young adults, but that ii) higher levels of cognitive reserve would moderate the relationship between age and task performance. Finally, our third experiment used an existing pool of research subjects with extensive neuropsychological and neuroimaging data already collected, to whom we administered the new task. If this task captures flexibility of solution strategy that may underlie CR, then we expected that task performance would i) correlate with proxies for CR and ii) account for variance in the performance of neuropsychological measures above that predicted by age and cortical thickness measures alone.

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Study 1

In the first experiment, we developed and administered an initial version of the Strategic Raven's Task (STRATA) to investigate its psychometric properties. Two groups of MTurk workers (young and old) were administered the task. We hypothesized that, consistent with previous research on task-switching, younger adults would have lower switch-costs than older adults both in terms of reaction time (RT) and in accuracy (ACC). More critically, this study intended to validate the notion of "strategy-shifting" costs; i.e., we hypothesized that subjects would perform worse (higher RT, lower ACC) on trials wherein they needed to employ the alternative strategy to the one used in the immediately antecedent trial. We expected that not only would strategy switch-costs be present, but also that older participants would show greater local and global switch-costs relative to young subjects.

Within task-switching paradigms, switch-costs come in a variety of forms and are often taken to reflect distinct cognitive processes engaged during the task. Global switch-costs have been speculated to reflect the setup costs incurred while scheduling two or more mental sets, as well as the additional burden on working memory to maintain these sets (Kray & Lindenberger, 2000). Local switch-costs are instead widely held to reflect executive processes required to deactivate a task set when moving from a trial where it was relevant to one where it no longer is (and to activate the relevant task set) (Monsell, 2003). Kray & Lindenberger (2002) used structural equation modeling to demonstrate that these two types of switch-costs do indeed reflect distinct processes. Further, study of these switch-costs in relation to aging have yielded mixed findings, but several rigorous meta-analyses have consistently found stronger age-related differences for global switch-costs than for local (with older adults usually incurring greater

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global switch-costs, and smaller local switch-costs– or sometimes none) (Kray & Ferdinand, 2014).

A recent study that also included proxies for CR, found that older adults were impaired by greater local switch-costs, but not by mixing costs (Moretti, Semenza, & Vallesi, 2018); furthermore, one sub-scale of the Cognitive Reserve Index Questionnaire (CRIq) (Nucci, Mapelli, & Mondini, 2012), education, was found to moderate the effect of age on switch-costs (but not mixing costs). One possible explanation for the variability in findings is the suggestion that mixing costs only arise when a task employs bivalent stimuli – i.e., stimuli on which both tasks may potentially be executed (Mayr, 2001; Rubin & Meiran, 2005). Some have speculated that inclusion of bivalent stimuli in one task induces “cautious responding” on other tasks within the same block, even when they use univalent stimuli (Metzak, Meier, Graf, & Woodward, 2013; Woodward, Meier, Tipper, & Graf, 2003). This so-called bivalency effect is especially present in younger adults (Rey-Mermet & Meier, 2015). Hirsch et al. (2016) found no age differences in mixing costs when univalent stimuli are used. Mixing costs are also typically absent without overlapping stimulus-response (S-R) representations; i.e. if responses are mapped differently for each task or stimuli do not cue a competing representation (Mayr, 2001). Given these observations, we expected that switching strategies within our paradigm would induce global and local switch-costs and that these costs would be exaggerated among older subjects, but such switching would be less subject to mixing costs given the nature of the stimuli (where only one of the two strategies could be employed).

Switch-costs are calculated by contrasting accuracy or RT across two conditions (e.g., non-switch versus switch trials within a mixed block or non-switch trials in a mixed block versus

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non-switch trials in a pure block). While prevalent, and useful for pointing to which aspects of cognition may most contribute to impaired performance, switch-costs' reliance on difference scores is problematic because of the comparatively low reliability of difference scores (Cronbach & Furby, 1970). Based on how difference scores are calculated, it is a mathematical necessity that if the two component scores are highly correlated (which we would expect given they are measured within-subjects and likely reflect similar mental processes), the reliability of the difference scores will be low (Draheim, Hicks, & Engle, 2016). Another problem with difference scores relates to individual differences in the aspects of a task deemed most important, both explicitly and implicitly. switch-costs, whether on the global or the local level, do not consider individual differences in the speed-accuracy trade-off; while some individuals may give preference to speed, others may prioritize accuracy.

To address these potential problems with common switch-cost metrics, we utilized an approach to collapsing speed and accuracy components of switch-costs into a single integrated metric. Doing so helps to reduce the number of statistical tests necessary, while also avoiding some of the challenges of difference scores such as low reliability (see for discussion Hughes, Linck, Bowles, Koeth, & Bunting, 2014). Following Vandierendonck (2017) we computed each subjects' linear integrated speed-accuracy score (LISAS) to represent their typical RT during a switch trial corrected for the number of errors they commit across all conditions. This integrated measure has been shown to perform well relative to other similar measures in its power to detect actual effects and to avoid Type-I errors, in both simulation studies and re-analyses of task-switching data (Vandierendonck, 2017, 2018). We hypothesized that older adults would display

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overall higher LISAS scores (reflecting worse overall performance), but that education would moderate the effect of age on LISAS score.

1.1 Methods

1.1.1 Participants.

Participant characteristics are given in Table 1.

Participants were recruited via Amazon's Mechanical Turk platform. Thirty-seven young (20-40 years) and thirty-one old (60-80 years) subjects took the task over a period of 2 weeks. To be eligible, all participants had to be native English speakers and reside in the US. Subjects also completed a pre-study questionnaire asking them to report their age, gender, and years of education. The entire duration of the task was approximately 25 minutes, and subjects were compensated \$3 for their participation.

Sample size was estimated using a priori power analysis conducted using the "pwr" package run with the R statistical software, with expected effect size equal to .65 as this has been observed in prior studies investigating multi-way interactions among age, condition type, and inter-subject measures (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001). We also used a significance level of 0.05 and a power level of 0.80.

Studies of MTurk samples show generally good validity and reliability. Such samples generally compare well to more typical samples in terms of psychometric properties (Behrend, Sharek, Meade, & Wiebe, 2011; Buhrmester, Kwang, & Gosling, 2011), have comparable levels of attention to undergraduate convenience samples (Chandler & Shapiro, 2016; Hauser & Schwarz, 2016), and have been found to accurately reflect their reported demographics (2012).

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Furthermore, as compared to typical convenience samples such as undergraduate students, MTurk workers display higher levels of demographic and psychometric diversity (Rand, 2012). While this worker pool tends to be slightly more educated than the general population, and typically has a higher representation of males (Berinsky, Huber, & Lenz, 2012), MTurk samples have been widely used to replicate research findings previously demonstrated in more typical samples (Gandullia, Lezzi, & Parciasepe, 2020; e.g., Heer & Bostock, 2010; Ong, IJzerman, & Leung, 2015).

1.1.2 Material.

Task design. The online supplement describes the development and norming of the test items used in this and subsequent studies. Normed items described by Matzen et al. (Matzen et al., 2010) were incorporated into an 80-item computerized Strategic Raven's Task (STRATA). The task was programmed using the PHP: Hypertext Preprocessor (PHP) programming language and displayed four blocks of twenty trials each. The first block consisted entirely of logico-analytic strategy items, displayed in a pre-randomized order fixed for all participants. The second block contained a mix of logico-analytic and visuospatial strategy trials, again randomized but fixed across subjects; there were an equal number of each problem type, and the block was designed to include 9 "switch" trials (i.e., trials wherein subjects have just completed a trial of the alternate strategy type and now they are seeing the other one) and 11 "non-switch" trials. The third block contained exclusively visuospatial strategy trials but was otherwise identical in structure to the first block, while the fourth block was again mixed and identical in structure to the second block.

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An example of each problem type is shown in Figure 1. Figure 2 displays the block structure of the task.

Each trial was preceded by a 500-ms inter-trial-interval (ITI), and the trial ended either when participants entered a numeric value from 1 to 8, representing their answer to the problem, or after 30-seconds elapsed without a response. In the latter case these trials were coded as “Time-Outs.” For each item, accuracy, and RT (in milliseconds) were recorded.

Pre-Study Screening Questionnaire. A basic pre-study screener was administered to all participants asking them to enter their assigned subject ID, their age in years, their years of education, their biological sex (male or female), and whether English was their native language.

1.1.3 Procedure.

Participants were recruited via Mechanical Turk and linked directly to the URL for the study, where they viewed an informed consent form before completing the screening questionnaire.

Following the questionnaire, participants viewed the instructions for the task. They were instructed to complete each item by finding the pattern in the matrix, and to select the answer choice that best completes the pattern. They were then given four self-paced practice trials, with two examples of each item type (visuospatial and logico-analytic). For each practice item, detailed feedback about the series of necessary steps to solve the item were shown to participants after each incorrect response. Following practice, participants were instructed that they would have a 30-second time limit on each problem, so they had to work as quickly as possible on each problem without sacrificing accuracy. They indicated when they were ready to commence the

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task with a press of the space-bar. Between blocks 2 and 3, participants were presented a screen with a visible two-minute countdown timer and told that they could rest for this time or press a key to continue with the final two blocks. Following the last block, participants were thanked for their participation and their study compensation was automatically released.

1.1.4 Data analysis.

Prior to RT analyses, all RTs for incorrect responses were excluded from the data set. For correct responses, all RTs shorter than 300ms were removed due to the high likelihood of their resulting from anticipation errors or other task-irrelevant features such as subject inattention/distraction (Luce & others, 1986; Whelan, 2008). All correct RTs falling above or below 2 SDs of each subject's mean RT were also excluded. This filtering allowed us to maintain high response levels while lowering the probability of committing Type II-errors with the inclusion of subject-specific outliers. Although many candidates for RT outlier detection have been proposed, a recent simulation study compared rates of bias induced by these methods, with bias measured in terms of the deviation of proportion of significant differences found in a simulated dataset following various outlier exclusion methods from that proportion in an “uncontaminated” sample of data in which no outliers were incorporated. This analysis found that excluding outliers based on z-scores/SDs resulted in the least bias, in terms of minimizing Type-I and Type-II errors, and led to the removal of relatively few values as compared with several more complicated treatments (Berger & Kiefer, 2021).

Switch-costs. Analyses were conducted on two separate dependent measures: reaction time (RT) and accuracy (ACC). To ensure the non-normal distribution of the percentages would not impact the analyses, we also computed the arc-sin transform of the ACC measure, and replicated

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each analysis using both variables (we report only results of the initial models, since these were identical to the arc-sin models).

Three types of switch-costs were examined: 1) global, 2) local and 3) mixing costs. Global switch-costs are measured by comparing performance on blocks with just one strategy type (a “pure block”) to those with two strategy types (“mixed block”). Measuring them involves utilizing block-type alone as the within-subjects factor. Local switch-costs are measured by comparing performance, within a single mixed block, when moving between two trials of the same strategy type and two trials different strategy types. Thus, switch-type is used as the within-subjects factor (again, within mixed blocks only). Mixing costs are measured by comparing change in performance across nonswitch trials (i.e., a trial that was preceded by a trial with the same strategy type) within a pure block to nonswitch trials within a mixed block. Thus, measuring them involves utilizing block-type as the within-subjects factor among nonswitch trials only.

The initial set of models used a 2x2 repeated-measures ANOVA, with one between-subjects factor (age group: young vs. old), as well as one within-subjects factor: either block-type (mixed vs. pure) for global switch-costs and mixing costs, or switch-type (switch vs. nonswitch trial) for local switch-costs. This comprised a total of six ANOVAs, with three for each of the outcome variables tested (ACC, RT) and four total using block-type as the within-subjects factor whereas two used instead switch-type. The level of significance for each was set at .05.

LISAS Scoring. Integrated speed-accuracy scores were calculated by multiplying each subject’s mean proportion errors (PE) during switch trials by the ratio of their overall task standard deviation in RT to their overall task standard deviation in PE, and then adding their

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mean switch trial RT (for correct trials only). The resulting score can be interpreted as the subject's typical RT on switch trials corrected for their overall number of errors.

LISAS scores were compared for young versus old subjects using an independent T-test. The potential role of education was tested using linear regression with age group, education, and the interaction of age group with education as predictors and LISAS as the outcome measure.

1.2 Results

T-tests were used to confirm that the covariates were not significantly different in each group. Error rates were on average low. On average, older adults displayed more errors than younger adults. Older adults demonstrated greater reaction times depending on block-type, with the largest RTs being observed in mixed blocks; in contrast, young adults' RTs were only slightly increased in mixed blocks. Comparison of block-level and trial-level RTs by age group is shown in Figure 3.

1.2.1 Global (Block-Level) Switch Costs.

To investigate global switch-costs, two mixed ANOVAs were conducted, one for RT and one for ACC, with age group as the between-subjects factor and block-type as the within-subjects factor. Analysis of RT showed a significant main effect of block-type, $F = 50.906$, $p < .05$. Age group, and the interaction of age group with block-type, were not significant ($F = 1.233$, and $F = 2.21$, respectively).

Analysis of ACC showed a main effect of age group, $F = 53.73$, $p < .05$, as well as a significant interaction between age group and block-type ($F = 7.736$, $p < .05$). Older subjects had greater overall costs to ACC when comparing mixed blocks to pure blocks, relative to young

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subjects who had smaller differences. Block-type alone ($F = 8.905$) by contrast did not result in a significant main effect.

1.2.2 Local Switch Costs.

To investigate local switch-costs, two mixed ANOVAs were conducted controlling for the impact of block-type on both reaction time and accuracy using a 2 (age group: young or old) by 2 (trial-type: switch or nonswitch) design. Analysis of RT found significant differences associated with trial-type (switch or nonswitch), $F = 5.95$, $p < .05$. No significant main effect of age-group, or interaction effect between age group and trial-type, was observed. Analysis of ACC found a significant main effect of age group ($F = 3.357$, $p < .05$). The main effect of trial-type, and the interaction between trial-type and age group, were not significant.

1.2.3 Mixing Costs.

Mixing costs were assessed by controlling for the trial type factor. A 2 (age group: young or old) by 2 (block-type: mixed or pure) mixed design was conducted exclusively among nonswitch trials. Results of the ANOVA of RT values revealed a significant main effect of block-type ($F = 35.262$, $p < .05$), but age group and age group * block type were not significant.

ANOVA results for accuracy again demonstrated the opposite pattern as those for RT; block type alone was not a significant main effect, yet age group ($F = 28.58$) as well as the interaction of age group with block type ($F = 4.07$) were both significant ($p < .05$). Older subjects experienced greater mixing costs to ACC relative to young subjects. Both gender and education displayed low and non-significant correlations with RT and ACC.

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1.2.4 LISAS Measure.

LISAS scores were significantly different between the young group and the old group ($t = 11.247$, $p < .0001$), with better performance among the younger group. Education was not significantly correlated to the LISAS measure.

Within the regression model, neither of the main effects were significant, nor did the interaction term reach significance.

1.3 Discussion

Results from the first experiment served to validate our assumption that strategy-switching can be studied within the context of a task-switching paradigm. The older adults in this study tended to have higher RTs and lower ACC overall, and moreover had higher mixing costs than young subjects. This is consistent with the literature on task-switching across aging and is often speculated to result from differential neural recruitment in response to such sudden and sometimes unexpected shifts in task requirements (Travers & West, 2008; West & Travers, 2008). Even with high stimulus latency and more complex reasoning problems represented, these established observations from standard task switching studies held in our first study.

The experiment also had several limitations, however. The first was that we did not capture the cognitive status of the participants, a status which possibly could be at pathological levels more frequently among the older adults, skewing the performance results. Moreover our lone reserve proxy for this study, years of education, did not correlate with performance. We suspect this was likely due to the limited characterization of this factor and so collecting multiple

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more standardized measures of CR and testing their interaction with overall strategic flexibility became a major goal for our next study.

Another major limitation was the random and unpredictable ordering of the switch trials within mixed blocks, a factor which might have exacerbated the age effects for mixing costs in ACC (which we had expected to be minimized given the “univalent” nature of each stimulus) and incurred so-called “unexpected shift costs,” which may reflect separate cognitive processes than mixing costs and hence pose a threat of confounding our results (Van Asselen & Ridderinkhof, 2000).

Study 2

The second study was designed to replicate the effects observed in the first study, after controlling for potential cognitive impairment. Accordingly we collected two additional measures of cognitive status to screen out any subjects who show signs of impaired function. Additional questionnaires were also included to more fully estimate CR, and to examine the relationship between the integrated LISAS measure and CR proxies.

The STRATA task was also revised to match existing task-switching paradigms more precisely—specifically, stimuli ordering was reconfigured to correspond to the ‘alternating runs’ paradigm (Monsell, 2003). Commonly this paradigm is composed of alternating tasks consisting of a basic single step stimulus–response (S-R) trials, however as Rogers & Monsell (1995) noted, the precise definition of what constitutes a “task” within this paradigm is lacking. We expected that more complex Raven’s-type matrix problems within the alternating-runs paradigm would

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raise response times and possibly lower accuracy rates, but that switching between these strategies would result in similar switch-costs as seen using simpler tasks.

The introduction of the alternating-runs paradigm (as opposed to Jersild's (1927) original test-switching paradigm employing mixed blocks of the form ABAB which did not include any non-switch trials) allowed for more controlled observation of alternation or mixing costs. Normally, subjects are slower overall during such mixed blocks than they are during pure blocks, suggesting a global cost associated with switching tasks. Rogers & Monsell (1995) argued that global costs may reflect the additional working memory load necessitated by mixed blocks, and such costs may not be related directly to what was typically meant by task-switching. The alternating-runs paradigm attempts to correct for this potential confound by allowing direct comparison of such block-level global switch-costs, to performance costs associated with switch trials but not with non-switch trials within a mixed block. Such local switch-costs are closer in meaning to the original theoretical conception of task-switching. This paradigm has even been applied to more complex task sequences, so long as they are presented in a rigidly predictable order (Gotler, Meiran, & Tzelgov, 2003; Koch, 2001, 2005, 2008; Schneider & Logan, 2007), and hence is more appropriate for this particular task.

To examine interactions with additional covariates, this study utilized the integrated LISAS score as the outcome variable of interest. Given that the purpose of this study was to investigate expected relationships between task-switching ability and other covariates, we utilized this alternative method of scoring to explore how age and our lifetime exposure variables interact with strategy switching performance. We hypothesized that older adults would overall display

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higher LISAS scores (reflecting worse overall performance), but that our CR measures would moderate the effect of age on LISAS score.

2.1 Methods

2.1.1 Participants.

Demographic information for participants is shown in Table 2.

Participants were recruited via Amazon's Mechanical Turk platform. To be eligible, participants had to be native English speakers and reside in the US. Forty-eight young (20-40) and thirty-five old (60-80) subjects completed the task over a period of one month. Participants also completed a pre-study questionnaire asking them to report their age and gender. The entire duration of the task was approximately 30 minutes, and subjects were compensated \$4 for their participation. Informed consent was obtained at the beginning of the study.

Data from three young participants and one older participant were excluded for failing to complete the task. Additionally, one older participant was excluded for failing to respond to the majority (>90%) of trials. This left a final study sample of 45 young adults and 33 older adults.

2.1.2 Material.

Three measures were administered using Qualtrics.

AD8. The AD8 was administered as a screener for participants exhibiting signs of cognitive impairment, ensuring that any age effects observed derived from normal cognitive aging rather than pathology. This brief (8-item) test probes memory, orientation, judgment, and function, and showed good sensitivity (86%) and specificity (74%) to Alzheimer's disease in

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prior research (Galvin, Roe, Coats, & Morris, 2007). We utilized a conservative cut-off score of 2 on this test, excluding any participants scoring higher than this.

E-IADL. The extended instrumental activities of daily living (E-IADL) extend the predictive validity of typical IADL measures by incorporating several items related to leisure activities. While typical IADL measures are designed to detect cognitive risk-factors based on physical or cognitive impairments, the E-IADL is better equipped to detect risk factors based on activities corresponding to many of the intellectually stimulating exposure variables associated with CR (e.g. “gone to classes of any kind,” “club or center activities,” etc.). Prior investigation into this scale demonstrated both a severe decrease in ceiling effects (from 67% to 3%) over the typical IADL, and good predictive utility (Fieo, Manly, Schupf, & Stern, 2013). The sum of all items representing risk factors (e.g., endorsing difficulties performing chores without assistance) were subtracted from the sum of all items representing stimulating leisure activities (e.g., going to classes of some kind). All scores were individually standardized within age group (since older adults displayed higher levels in all measures as a function of more life experience), before being averaged for each participant. This measure was also used to screen out subjects at a high risk for cognitive impairment.

Lifetime experiences questionnaire (LEQ). Educational and Occupational sections of the LEQ were administered (Valenzuela & Sachdev, 2007). This questionnaire has been shown to produce a dominant factor with high loadings on education, occupation, and leisure activity, has strong correlations with tests of cognitive ability, and good predictive validity towards cognitive decline when applied to a sample of 18-month longitudinal data. It additionally allows the

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measurement of education and occupation values over a respondent's lifetime rather than statically.

Using the LEQ items, we computed a composite CR-proxy score designed to quantify the level of complex cognition participants had engaged in throughout their lifetimes. For education, total years endorsed of primary and secondary education were totaled, and to this we added the higher-weighted years of post-secondary education endorsed, weighted by 1) percent of coursework completed and 2) enrollment status (half-time was weighted by .5). To this was added the years of professional or graduate education, weighted by a factor of 1.5 to reflect the additional cognitive demands of this track, and additionally weighted by percent completed and enrollment status. For occupation, each subject's reported occupation was matched to the closest available occupation in the Dictionary of Occupational Titles (DOT), which provides complexity scores along the dimensions of work with data (ranging from "comparing" to "synthesizing"), people (ranging from "taking instructions" to "mentoring"), and things (ranging from "handling" to "setting up").

Cross-correlations within and between covariates are reported in Table 3.

2.1.3 Procedure.

Revised STRATA Procedures. Based in part on our findings from Study 1, the STRATA task was redesigned to match the structure of a typical task-switching paradigm more precisely. This version of the task was programmed using the jsPsych Javascript library (de Leeuw & Motz, 2016), which allowed it to be directly accessed via a web browser just as the PHP version had been. Most importantly, stimuli in the mixed blocks were reordered to follow an alternating-runs structure, wherein a task (strategy)-switch is induced after every two successive trials, i.e. trial

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order became: A,A,B,B,A,A,B...(Monsell, 2003). The task was also altered to allow for a completely randomized presentation of block orders, guarding against any accidental effects from subjects being exposed to a pure block first.

Participants recruited via Mechanical Turk were linked directly to the URL for the study, taking them to a Qualtrics survey where they viewed an informed consent form before completing the questionnaires followed by the task. As in Study 1, they first saw the instructions for the task. They were instructed to complete each item by finding the pattern in the matrix, and to select the answer choice that best completes the pattern. They were then given four sample trials, with two examples of each item type (visuospatial and logico-analytic). For each self-paced practice item, detailed feedback about the series of necessary steps to solve the item were shown to participants after each response, regardless of initial accuracy. This was done to ensure that participants had explicit knowledge of the types of strategies available to them. Following the practice, participants were instructed that they would have a 30-second time limit on each problem, so they had to work as quickly as possible on each problem without sacrificing accuracy. They indicated when they were ready to commence the task with a press of the space-bar. Between each trial, a fixation cross was displayed in the center of the screen for the 500ms ITI. Between each block, participants were presented a screen telling them that they had 1 minute to rest, and told that they could rest for this time, or press a key to continue with the next block. This was done to reduce cognitive fatigue. Following the task, participants were thanked for their participation and their study compensation was automatically released.

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2.1.4 Data analysis.

LISAS Scoring. Integrated speed-accuracy scores were calculated following the same procedure described in Study 1.

Testing for Moderation. To determine if the effect of age on task performance was affected by participants' CR, regression analyses were conducted using LISAS as the dependent measure, participants' raw age in years as the independent measure, and the composite CR measure as a covariate. Both CR and age in years were mean-centered prior to being included in the analysis.

2.2 Results

Comparison of block-level and trial-level RTs by age group is shown in Figure 4.

2.2.1 Speed-Accuracy Integrated Scores (LISAS).

A t-test revealed that LISAS scores significantly differed between the young and old groups ($t = 10.286$, $p < .0001$), with younger subjects outperforming the older group.

CR and LISAS were significantly correlated ($r = -0.381$, $p < .001$), with higher CR resulting in lower integrated scores/better performance.

2.2.2 Moderation.

Results of a linear model using LISAS as the dependent variable and including age in years, the CR composite, and the interaction of CR with age covariates showed that this model was statistically significant overall ($F = 18.24$, adjusted R-squared = 0.418, $p < .0001$). Age was significantly related to LISAS score ($t = 5.447$, $p < .001$), with increasing age resulting in a higher LISAS (i.e., lower performance). CR was also significantly related to LISAS score ($t = -$

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3.423, $p < .001$), such that higher levels of CR were associated with lower LISAS. The interaction of age with CR was not statistically significant, however.

2.3 Discussion

The second study largely replicated the effects of the first, and explored the role of CR as a predictor of the integrated speed-accuracy score. Results of the linear model suggest that accounting for participants' CR, as estimated using education and occupation components of the LEQ, could account for task performance independent of age. Age overall was predictive of higher LISAS scores—representing lower performance on the STRATA task—but higher levels of CR were associated with better LISAS scores. These results suggest that strategic flexibility itself can be interpreted as a cognitive outcome subject to age-related changes, but that higher CR may serve to maintain such flexibility.

Use of the integrated speed-accuracy scores allowed us to look at covariates in a straightforward manner. CR was significantly predictive of strategic flexibility performance, suggesting a relationship between these constructs. However, as argued by Stern et al. (2020), a simple correlation between some measure of cognitive performance and a sociobehavioral proxy of CR is not sufficient evidence that the measure is reflective of CR. Demonstrating that STRATA performance can account for variability in an independent measure of cognitive/clinical outcome beyond what is explained by age or brain measures alone was therefore the major goal of our final reported study.

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Study 3

In our final study, we administered the STRATA to a group of subjects who had participated in a study at Columbia University Medical Center. We were therefore able to utilize a rich existing set of data from these subjects. This included a thorough neuropsychological battery, a more detailed composite measure of their estimated CR, and their values for various structural MRI measures including cortical thickness measures and total gray matter volume. Here we expected to replicate the prior behavioral effects observed in Studies 1 and 2, but also to explore the relationship between STRATA performance and neuropsychological scores as well as MRI measures. We hypothesized that STRATA integrated performance scores would contribute to explaining variance in cognitive performance above and beyond cortical thickness and that this should be especially true for older adults. Given the same brain structure, a higher level of cognitive flexibility—here operationalized as STRATA performance, or the ability to quickly and accurately switch the application of solution strategies based on the trial or task at hand—may allow some individuals to better utilize whatever extant neural structure they have, improving cognitive performance relative to those with equal brain structure but lower cognitive flexibility.

3.1 Methods

3.1.1 Participants.

Demographic information for participants is shown in Table 4.

Participants who had participated in the Reference Ability Neural Network (RANN) study were recruited (Habeck et al., 2016; Stern et al., 2014). These participants had been recruited into the parent study using market-mailing procedures designed to equalize the recruitment approaches across age. Those who responded to the mailing were screened over the phone to

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ensure that they were right-handed, English was their first language, they had no recent history of neurological disorders, were not currently taking psychotropic medications, and their vision was normal or corrected-to-normal. Participants meeting these basic inclusion criteria were then tested in person with an extensive neuropsychological battery and a series of imaging studies. Global cognitive functioning was assessed with the Mattis Dementia Rating Scale, on which a score of at least 130 was required for inclusion (Mattis, 1988).

Recent participants in the RANN study were invited to participate in the present study. This STRATA study was approved by the Internal Review Board of the College of Physicians and Surgeons of Columbia University. Written informed consent was obtained from all participants prior to study participation, and participants were compensated \$20 for their participation in the STRATA study. Forty-four young (20-40) and forty-two old (60-80) participants took part in the current study.

3.1.2 Material.

Cognitive Measures and CR Proxy Score. Previous factor analyses from our laboratory identified neuropsychological measures underlying three cognitive domains: memory, processing speed/attention, and fluid ability (Salthouse et al., 2015). Fluid ability was defined as the composite score comprising the Letter-Number Sequencing, Matrix Reasoning, and Block Design subtests of the WAIS-3 (Wechsler, 1997). Memory was defined as the composite score of three sub-scores of the Selective Reminding Task (SRT)—total, delayed recall, and delayed recognition (Buschke & Fuld, 1974). Processing speed was defined as the composite score of performance on the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler (1997))

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Digit Symbol subtest, the Trail Making Test Form-A (Reitan, 1958), and color-naming from the Stroop test (Golden & Freshwater, 1978).

The cognitive reserve proxy score consisted of the composite score comprising years of education and scores on two IQ indices: the NART (Nelson & O'Connell, 1978) and WAIS-R vocabulary score (Wechsler, 1997). Previous work from our laboratory has demonstrated the validity of this construct using these cognitive tests (Siedlecki et al., 2009).

3.1.3 Procedure.

Image Acquisition. MRI images were acquired in a 3.0T Philips Achieva Magnet using a standard quadrature head coil. A T1-weighted scout image was acquired to determine subject position. One hundred sixty-five contiguous 1 mm coronal T1-weighted images of the whole brain were acquired for each subject with an MPRAGE sequence using the following parameters: TR 6.5 ms, TE 3 ms; flip angle 8°, acquisition matrix 256x256 and 240 mm field of view. A neuroradiologist reviewed anatomical scans, and any with potentially clinically significant findings (such as abnormal neural structure) were removed from the sample prior to analysis.

Cortical Thickness - Using each individual's T1-weighted MPRAGE image, a structural imaging measure of mean cortical thickness was derived using FreeSurfer software (<http://surfer.nmr.mgh.harvard.edu/>). Cortical thickness was measured by first reconstructing the gray/white matter and CSF/gray matter boundaries (Dale, Fischl, & Sereno, 1999) as the cortical surfaces, and then calculating the distances between these surfaces at each point across the cortical mantle. The maps produced are capable of detecting sub-millimeter differences between groups (Fischl & Dale, 2000). We manually check the accuracy of the spatial registration and the

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white matter and gray matter segmentations following the analytic procedures outlined in Fjell et al. (2009). Mean total cortical thickness was used in the present analyses.

STRATA Administration. Participants took the STRATA task online. After providing informed consent via Qualtrics, they were directed to the task directly in their web browser. They were instructed to take the task on a laptop or desktop computer with a full screen, and to ensure that they could work continuously on the task in a distraction-free environment for at least one hour. The same procedures as Study 2 were used.

3.1.4 Data analysis.

LISAS Procedure. The integrated speed-accuracy score was performed as described in Study 1, resulting in a single score per subject representing RTs on switch trials corrected for overall error rates.

Bivariate Brain Correlations. We conducted a series of bivariate correlations designed to measure the relationship between cognition on the one hand, and LISAS score, age, cognition, and brain structure, respectively.

Cognition was operationalized as the neuropsychological composite scores in the following domains: Fluid ability, processing speed/attention, memory, and global cognition (a composite measure of these individual domains). Brain structure was operationalized as total gray matter volume as well as various regional cortical thicknesses derived using Freesurfer software.

Direct effect and Moderation Analyses. Analyses were conducted to test whether the relationship between brain structure and cognition is significantly impacted by the inclusion of LISAS score in our models. These analyses used the interaction of mean cortical thickness by

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LISAS score as their independent variable, i.e.: Cognition = [mean cortical thickness + LISAS + mean cortical thickness * LISAS]

3.2 Results

3.2.1 Bivariate Correlations.

The LISAS integrated score was not significantly related to age group ($t = 1.5263$, $p = 0.1311$). However it did correlate significantly with total gray matter volume ($t = -2.3205$, $p = 0.023$), as well as with the neuropsychological composite score in Reasoning ($t = -5.2911$, $p < .001$) and Processing Speed ($t = -2.8585$, $p = .005491$). The correlations between LISAS and the Memory composite score did not reach significance ($t = -1.9126$, $p = 0.05957$). These results matched our expectations that those with higher levels of cognitive performance would exhibit greater performance (lower LISAS scores), as would those with greater total gray matter volumes.

Correlational analyses were also conducted between the LISAS scores and our CR composite measure. This correlation was highly significant ($t = -10.337$, $p < 0.001$). Figure 5 displays LISAS scores against standardized CR by age group.

The correlations between each composite and LISAS, as well as inter-composite correlations are displayed in Table 5.

3.2.2 Test of Direct Effects and Moderation.

We conducted a series of regression models testing the direct effect of cortical thickness and LISAS score, as well as their interaction, on cognitive performance. Global cognitive performance was significantly related to both LISAS ($T = -6.8974$, $p < .0001$), and mean cortical thickness ($T = 3.2643$, $p = 0.0017$), but the interaction of cortical thickness and LISAS was not

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significant. The significance of the LISAS predictor in this model indicates that the overall strategic flexibility contributes to overall neuropsychological performance after accounting for the effects of cortical thickness. In exploring these relationships in specific cognitive domains, for fluid ability, LISAS scores were also a significant predictor of performance ($T=-5.6312$, $p<.0001$) in addition to mean cortical thickness ($T=2.5297$, $p=0.0135$) but there was no interaction. For processing speed/attention, a significant main effect of LISAS was observed ($T=-2.5895$, $p=0.0116$), as was a main effect of mean cortical thickness ($T=3.3921$, $p=0.0011$), but again this interaction was not significant. For memory, only a direct effect of mean thickness was observed ($T=3.8007$, $p=0.003$).

3.3 Discussion

Results of the third study replicated some findings of Studies 1 and 2, with older adults displaying poorer performance relative to younger adults, and all participants showing greater RTs in mixed than in pure blocks. There was high correlation between the LISAS measure and a composite proxy for CR, suggesting that the two measures are related. Further, while this integrated performance measure was not shown to moderate the effects of cortical thickness on global cognition or any of the specific cognitive domains, it did significantly account for variance in global cognition, processing speed, and fluid reasoning over and above cortical thickness. These findings suggest that this measure of cognitive flexibility behaves similarly to other mechanisms and neural networks associated with CR.

Several reports have illustrated that CR can also moderate the relationship between brain-based biomarkers and cognitive outcomes. Steffener et al. (2014), for example, found that estimated CR moderated the effect of cortical thicknesses in select regions of the brain on fluid

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reasoning performance: higher CR allowed for the utilization of existing neural tissue and resulted in better than predicted performance relative to those with low CR. Similarly, Stern et al. (2018) showed that a “task invariant” activation pattern associated with IQ moderated the effect of cortical thickness on cognitive performance. While we hypothesized that the STRATA performance might behave in a similar way, we instead observed that the integrated score on this task is highly predictive of cognitive performance across multiple domains, even after controlling for the effects of cortical thickness. As Stern et al. (2020) have argued recently, finding associations of a proposed index of CR with cognitive outcomes after partialling out the effects of brain measures linked to age-related deterioration should be considered evidence that the new measure may reflect CR.

General Discussion

While many studies have attempted to use functional imaging to identify the “neural implementation” of cognitive reserve, relatively few studies have focused on cognitive experimental approaches for identifying potential mechanisms underlying CR. Further, many imaging studies have addressed aspects of network efficiency or capacity as potential mechanisms underlying CR, but have not addressed flexibility of solution strategy. Here we aimed to derive a measure of strategic flexibility by combining a well-understood fluid reasoning task with a task-switching paradigm. Investigating strategies can be methodologically challenging since every instantiation may be unique across a task and simultaneously involve various disparate and neuroanatomically distinct cognitive processes. We therefore chose a task where the solution strategy for each item is highly constrained, and focused on flexibility in solution strategy, operationalized as the ability to switch between strategies based on task demands.

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Previously we attempted to investigate flexibility within the context of a strategy selection task, i.e., a computational estimation task requiring alternation between two arithmetical strategies with a mathematically optimal and sub-optimal solution (D. J. Barulli, Rakitin, Lemaire, & Stern, 2013b). Although an association between CR and performance was observed using this task, the properties of the stimuli made interpreting the underlying cognitive process difficult. The significance of the current series of studies lies in its extension of this previous research to task items whose solution strategy is well established, embedding these items within the similarly well-established task-switch paradigm, and directly testing whether they contribute to better performance after controlling for structural brain status.

Results of Study 1 confirmed our hypothesis that strategy-shifting within a single task would result in switch-costs. Subjects were slower at making selections in switch trials, and they showed decreased accuracy during these trials. Results here indicated that older adults showed even more marked mixing costs in error rates than young adults, a finding surprising to us given the univalent nature of the stimuli employed. Despite this, we could not find statistically significant evidence for our hypothesis that older adults are slower on switch trials than on non-switch trials within mixed blocks. While performance on mixed blocks was overall slower, particularly in the old group, than on pure blocks, RTs on the switch trials within any given mixed block did not significantly differ from those of the nonswitch trials.

One potential explanation for this lies in the conflicting pattern of results observed for reaction time and accuracy; among all analyses assessing global switch-costs, local switch-costs, or mixing costs, age group and its interaction with the within-subjects factor were only significant predictors of accuracy, not reaction time differences. Because this pattern raises the implication

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of a speed-accuracy trade-off, we also utilized an alternative scoring approach that combines both speed and accuracy and has the advantage of better statistical reliability. As expected, LISAS scores were significantly higher among older adults, suggesting poorer strategy-switching ability.

Results of Study 2 replicated the findings of Study 1, with older adults again displaying poorer integrated performance scores as well as greater impairment to performance in mixed blocks relative to younger adults. Additionally, the high correlations between the LISAS metric and estimated CR support the idea that STRATA captures a mechanism underlying CR. In a linear model, age and CR were both related to performance and, although the interaction between age and CR did not reach statistical significance, its marginal significance is an encouraging sign that CR can be associated with better strategic flexibility with advancing age.

Results of the final study further extended the parallels between CR and strategic reasoning by looking at interactions with brain-based measures such as cortical thickness. Although not a successful moderator of the relationship between cortical thickness and cognition, STRATA performance contributed additionally to variance in performance over and above cortical thickness alone for total cognition, processing speed, and fluid reasoning. This corresponds closely with what has been observed in other studies of potential mechanisms of CR, such as a task-invariant network and potential resting-BOLD networks that have been associated with reserve. In general, as cortical thickness decreases with age it impacts cognitive performance; however as with CR more generally, elevated STRATA performance can be interpreted as reflecting some increased level of strategic flexibility capable of preserving cognitive performance in the face of this age-related brain change.

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These findings suggest that strategic flexibility behaves similarly to neurofunctional mechanisms of CR, and hence may itself function as another such mechanism. Strategic flexibility, like cognitive flexibility more broadly, may itself be subject to age-related performance effects, and indeed several of our findings point towards this conclusion. However, at any age individual differences in strategic flexibility can serve to moderate the impact of age- or disease related changes. This parallels research utilizing neuroimaging approaches to identify functional patterns that may underlie CR in that their expression moderates between structural brain change and cognition. (Stern et al., 2020).

More research is required to fully elaborate on how performance on flexibility tasks is best modeled – potentially as both a downstream effect of aging as well as a moderator of previously identified age-cognition relationships (e.g., using moderated-mediation analyses). Although cognitive flexibility is often studied within the context of “top-down” executive control theories that may inherently assume decreased flexibility with advancing age, alternative explanations for this concept are possible. Some authors have argued that cognitive flexibility can instead be modulated via “bottom-up” associative learning mechanisms, and that its behavior may be heavily dependent on the context of the task employed including its reward schedule (Braem & Egner, 2018).

One interesting extension of the methods employed would be to investigate STRATA performance within the context of neuroimaging. We might expect that each of the two solution strategies would be associated with a specific pattern of task-related activation, thus potentially providing the ability to image flexibility of solution strategy. As suggested above, decomposition of existing tasks into strategic components has been perhaps most instructive when it has

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demonstrated that group-wide activation differences may derive from differential strategy use, rather than from cognitive deficits or mostly static individual differences.

Versions of the STRATA might also be designed which utilize “bivalent” stimuli to further probe the relationship between age and strategy mixing costs. The stimuli initially generated and chosen for inclusion were designed intentionally to be most effectively solved using only one of the two broad strategies available (visuospatial or logico-analytic). This was meant to eliminate the need to rely on post-test self-reports of each subject’s strategy use, which may be inaccurate or vague and may also fail to adequately capture within-item shifting which is known to be impacted by aging (Ardiale & Lemaire, 2012). However, RPM stimuli that are more readily subject to both sets of rules and hence would be inline with bivalent stimuli have also been identified (Carpenter, Just, & Shell, 1990). Based on the existing literature we would expect inclusion of these item types to further exacerbate mixing costs in general and in older subjects especially.

In summary, the STRATA task presents a novel method of studying flexibility of solution strategy which may shed light on the relationship between flexibility of solution strategy and CR. Our results suggest that strategic flexibility may be one mechanism through which CR lends protection against decline, allowing some older adults to maintain cognitive performance with more optimal utilization of the best strategy across changing task demands. What remains to be investigated is whether promoting strategic flexibility can result in more successful cognitive aging.

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ASSESSING STRATEGIC FLEXIBILITY

Table 1

Study 1 participant characteristics.

Variable	Young Group (n = 37)	Old Group (n = 31)
Age (years)	26.54 (7.81)	67.09 (7.38)
Female, n (%)	22 (59%)	20 (65%)
Education (years)	14.09 (2.34)	14.51 (1.98)
ACC	.793 (.40)	.694 (.45)
RT	11705 (2464)	12074 (768)
LISAS	12835 (2199)	13307.58 (3950)

ASSESSING STRATEGIC FLEXIBILITY

Table 2

Study 2 participant characteristics.

Variable	Young Group (n = 45)	Old Group (n = 33)
Age (years)	34.26 (7.81)	61.5 (3.12)
Female, n (%)	13 (28.9%)	17 (51.5%)
AD8	0.356 (0.57)	0.667 (0.78)
E-IADL	2.87 (1.08)	2.06 (1.50)
Education (raw years)	14 (5.6)	18.4 (6.3)
Education (weighted score)	5.69 (1.05)	5.01 (0.951)
Occupation score	2.31 (1.93)	2.88 (1.53)
CR (standardized)	.733 (1.23)	.680 (1.04)
ACC	.839 (.368)	.815 (.398)
RT	12483 (512)	14942 (3711)
LISAS	12731 (1681)	15327 (3542)

ASSESSING STRATEGIC FLEXIBILITY

Table 3

Study 2 scores and correlations for CR proxy measures.

Variable	1	2	3	4	5	6	7	8	9
1. Age	1	--	--	--	--	--	--	--	--
2. AD8	0.219	1	--	--	--	--	--	--	--
3. E-IADL	-0.283*	-0.216	1	--	--	--	--	--	--
4. LEQ-Edu	-0.252*	-.229*	0.023	1	--	--	--	--	--
5. LEQ-Occ	0.135	-0.129	-0.028	.257*	1	--	--	--	--
6. CR Composite	-0.011	-0.206	-0.011	.661***	.895***	1	--	--	--
7. ACC	-0.036	0.172	-0.026	0.214	0.118	0.156	1	--	--
8. RT	-.329*	-0.048	0.072	-.246*	-0.154	-.315*	0.123	1	--
9. LISAS	-.288*	-0.021	0.033	-0.207*	-.201*	-.381**	0.096	.856***	1

ASSESSING STRATEGIC FLEXIBILITY

Table 4

Study 3 participant characteristics.

Variable	Young Group (n = 37)	Old Group (n = 31)
Age (years)	30.23 (5.63)	66.7(4.26)
Female, n (%)	17 (42.5%)	24 (60%)
Education (years)	16 (2.27)	16 (2.33)
NART	113 (8.78)	118 (9.39)
Mean Cortical Thx	2.68 (.0943)	2.56 (.116)
ACC	.746 (.394)	.649 (.280)
RT	10283 (3812)	12842 (5120)
LISAS	12520 (4733)	14340 (6588)

ASSESSING STRATEGIC FLEXIBILITY

Table 5

Study 3 scores and correlations for CR proxy measures.

Variable	1	2	3	4	5	6
1. Age	1	--	--	--	--	--
2. Edu	0.0154	1	--	--	--	--
3. NART	.228*	.592***	1	--	--	--
4. Mean cortical thx	-.573***	-0.022	-0.019	1	--	--
5. Total cognition	-.503***	.363**	.534***	.402***	1	--
6. LISAS	0.172	-.575***	-.728***	-0.186	-.634***	1

ASSESSING STRATEGIC FLEXIBILITY

Figure 1. Sample problems of each strategy type. On the left is a sample logico-analytic problem (requiring use of the “OR” rule). On the right is a sample visuospatial problem (requiring use of “Shading+Orientation” transformation).

ASSESSING STRATEGIC FLEXIBILITY

Figure 2. Stimuli ordering in a mixed block. L = logico-analytic problems. V = visuospatial problems. Red borders indicate a switch trial.

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Figure 3. Mean RT by block-type, trial-type, and age group in Study 1.

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Figure 4. Mean RT by block-type, trial-type, and age group in Study 2.

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Figure 5. Scatterplot of LISAS score against standardized CR by age group in Study 3.