Inhibition and Fraction Arithmetic: Insights from Heat-map Strategy Reports

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Abstract

Proficiency in math is critically important given its implications for education and daily life (e.g., finances, health). However, math is a challenging subject, and proficiency requires a complex interplay of content knowledge and general cognitive processes, including Executive Function (EF). In this exploratory study, we used heat maps to examine whether participants' self-reported attention to strategy-specific components of fraction arithmetic equations (i.e., operations, numerators, denominators) was related to their EF and task performance. Our results indicated that participants with stronger EF (indexed by a numerical stroop task) obtained higher fraction arithmetic scores and were also more likely to attend to strategy-specific components in the fraction problems. Additionally, a positive correlation was found between participants' selection of strategy-specific components and their fraction arithmetic accuracy.

Keywords: Fraction arithmetic; Strategy Reports; Executive Function; Inhibitory Control; Attention

Introduction

Executive Functioning and Math Performance

Executive Function (EF) refers to a set of cognitive skills that help guide goal-directed behavior. EF can be characterized as three separate, but related cognitive processes, which include updating/monitoring working memory, inhibitory control, and cognitive flexibility/shifting (Miyake et al., 2000). Although EF emerges early in development, it is thought to continue to mature into adolescence (Best & Miller, 2010). Prior research has found that EF is related to academic achievement, and in particular, EF skills have been implicated in math and reading achievement (Cortes Pascual et al., 2019; Kieffer et al., 2013; McClelland et al., 2007; St Clair-Thompson & Gathercole, 2006, for review see Zelazo & Carlson, 2020). A recent meta-analysis found that EF skills were correlated with both math (average correlation = .30) and reading (average correlation = .31) achievement across a wide age range (3-18 years) (Jacob & Parkinson, 2015).

Likewise, mathematical skills, such as those involving fractions, are considered high-leverage content that are related to positive life outcomes (e.g., access to college, graduation from college, financial success, life satisfaction; Bjalkebring & Peters, 2021; NMAP, 2008). Unfortunately, fraction understanding is challenging to acquire (Siegler, 2016; Siegler et al., 2013), people dislike fractions relative to other math content (Mielicki et al., 2021; Sidney et al., 2021), performance can be hampered by math anxiety (Mielicki et al., 2022), and people's confidence in their performance may not be aligned with their accuracy (Fitzsimmons et al., 2020a; Scheibe et al., 2022).

EF skills may be particularly important for math performance (see Cragg & Gilmore, 2014). Working memory is critical for learning new problem-solving strategies and holding intermediate problem-solving steps in mind (e.g., finding common denominators). Shifting is necessary when people encounter problems in which they need to switch between deploying several known strategies (e.g., fraction addition vs. fraction division; Fazio et al., 2016; Sidney et al., 2019).

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Inhibition has been a primary focus of recent studies, and it may play a critical role in performance across a variety of mathematical tasks (Gilmore et al., 2015). Inhibition of prepotent responses is required for people to perform accurately when reasoning about fractions (e.g., Gomez et al., 2015). For instance, because people have extensive experience with whole-number integers (Dehaene & Mehler, 1992), they often consider the independent components of fractions in isolation, rather than the holistic magnitude of the fraction (Alibali & Sidney, 2015; Ni & Zhou, 2005; Siegler et al., 2011). That is, they might focus separately on the 5 and 6 in the fraction ⅚, rather than the fraction's magnitude, .833. Furthermore, people may overextend whole-number operations when attempting to calculate fraction operations. For example, when attempting to solve a fraction addition problem, people may add numerators or denominators in isolation to generate their answer rather than add together the magnitudes of the two fraction addends (Siegler & Lortie-Forgues, 2015). To successfully reason about fraction magnitudes and operations, inhibitory control is a necessary cognitive process. Indeed, a numerical stroop task, in which participants judged the physical size of the single-digit numerical stimuli while inhibiting the magnitude of the numerals, was correlated with fraction estimation and magnitude comparison accuracy ($rs \geq .55$; Fitzsimmons et al., 2020b).

In the current study with adults, we anticipated that numerical stroop performance and fraction arithmetic performance would be related, given that both measures are correlated with estimation and magnitude comparison performance (Siegler et al., 2011). Furthermore, we explored whether adults' attention to components of fraction arithmetic equations (operations, numerators, denominators, which were measured via mouse click) reflected participants' problem-solving strategies.

Performance on Fraction Arithmetic

Children and adults frequently err when solving fraction arithmetic problems (Braithwaite & Siegler, 2018; Di Lonardo Burr et al., 2020; Siegler & Pyke, 2013; Siegler et al., 2011). According to the dynamic strategy choice account (Alibali & Sidney, 2015; Fitzsimmons et al., 2020b), participants' errors, which differ depending on operation types and whether the problems include common denominators, are evident in their performance and variable strategy reports. For example, people sometimes incorrectly operate across numerators and denominators in addition and subtraction problems with unequal denominators, or deploy strategies for other operations (e.g., inverting the second operand in a multiplication problem before multiplying).

Although strategy reports can yield valuable data providing important insights about participants' understanding as well as their misconceptions, coding open-ended strategy reports is time consuming, and it can be difficult to establish strong inter-rater reliability. Additionally, as many researchers are pivoting to remote data collection during the ongoing COVID-19 pandemic, alternative means to reliably collect strategy reports are needed. Various existing technologies may be employed to meet this need. In the present study, we begin to explore the Heat Map function in Qualtrics to provide support for the dynamic strategy choice account, specifically which fraction components participants report attending to, a proxy for their problem-solving strategies (for additional details see Method).

Current Study

The current exploratory study had three primary goals: (1) to explore whether inhibitory control, a component of EF, is related to adults' fraction-arithmetic performance, (2) begin foundational work utilizing online tools (i.e., Heat Maps) to measure participants' strategy variability, and (3) explore whether participants' attention to strategy-specific components of the fraction arithmetic equations (numerators, denominators, operation symbols) measured via mouse click are related to *both* their EF and fraction arithmetic performance. To this end, we presented adult participants with a series of cognitive tasks including a measure of EF (numerical stroop task) and fraction arithmetic problems in which participants were asked to click on the component they attended to *first*.

In line with prior research, we hypothesized that individuals with stronger EF skills would also exhibit higher accuracy on fraction arithmetic problems. Additionally, we anticipated that participants with stronger EF would be better able to inhibit attention to *non strategy-specific* fraction components and attend to *strategy-specific* components. While we hypothesized that across all test items participants should report attending to operations first, given that there are different procedures needed for each fraction operation, we also posited that unique attentional patterns could be deployed across operation types (addition/subtraction, multiplication, division), reflecting operation-specific strategies (see Method). Further, attention to strategy-specific fraction components was predicted to be positively correlated with fraction arithmetic performance. We also explored participants' confidence judgments on each fraction arithmetic problem and whether these ratings were related to their propensity to attend to strategy-specific (or non strategy-specific) fraction components.

Method

The results presented here are a subset of findings from a larger pre-registered study. These findings are novel and have not been published elsewhere.

Participants

Four hundred twenty-seven adults were recruited from Prolific, an online platform, to participate. Participants who did not complete the study were excluded from analysis; therefore, the final sample included 390 participants. Participants identified as: 41.9% male, 55.8% female, and 2.3% non-binary; 66.4% of participants had an associate degree or higher. Of those participants who reported their employment and income, 70.5% were employed and 59%

had incomes of $74,999 or less. Participants who reported their race self-identified as: 73.9% White, 6.7% Black/African American, 7.2% Asian, and 5.2% Hispanic/Latino. Participants received $13 for participation.

Procedure

Participants completed a series of online tasks administered via Qualtrics. The tasks included (among others) a math assessment on fractions, self-report attention measure, item-level confidence judgements, and a Numerical Stroop Task. Participants were able to skip individual items; accordingly, the sample size per item is variable. The study was self-paced.

Math Assessment Participants completed 24 fraction arithmetic problems: 6 items per operation (addition, subtraction, multiplication, division); operation order was blocked, and items were pre-randomized within each block. Eight of these test items were "critical trials" and were used to assess participants' fraction strategies. Critical trials included two test items per operation type, one with common denominators (e.g., $3/5 + 4/5$), and the other with different denominators (e.g., $2/3 + 3/5$). For all test items, participants solved each problem and then typed their answer in a response box. Note, participants were not required to reduce the fractions to their lowest terms. We calculated mean accuracy across all test items, the eight critical trials, and separately for each operation type.

Self-report Attention Measure: Selection via Mouse Click of the Operation Symbol and Strategy-Specific AOIs Recall that immediately before participants solved each of the eight critical test items, they were asked to select, via mouse click, the part of the problem they attended to first. For analysis, we created five Areas of Interest (AOIs) to code participants' mouse clicks. AOIs were drawn around each numerator, denominator, and operation symbol; see Fig 1. The AOIs were not visible to participants to avoid biasing their attention to specific parts of the equation. Participants could click anywhere on the display. Consequently, a sixth response category, "other," was coded which indicates a mouse click that did not occur in the five target AOIs. Therefore, for each of the critical trials, we could determine which of the following areas participants reportedly attended to first: Numerator 1 (top left), Numerator 2 (top right), Denominator 1 (bottom left), Denominator 2 (bottom right), Operation (middle), and Other. The task was designed such that participants were only able to make a single selection via mouse click. We were, therefore, able to assess the first part of the problem that they reported attending to, but not their sequential problem-solving steps, a point we return to in the Discussion. Note, that due to a technical error, for one test item, 36 participants were able to make multiple mouse clicks, and their responses for this item were excluded from analysis.

As noted previously, we anticipated that participants would look at the operation first to determine which strategy to deploy to solve the fraction arithmetic problems. Accordingly, for each critical test item, we coded whether participants clicked on the Operation AOI (scored as 1) or any other AOI (scored as 0). For each participant, we then created an average Operation AOI score, which reflected the mean number of times the participant selected the Operation AOI across the eight critical fraction arithmetic trials.

We also coded participants' operation-specific strategies, which were hypothesized to reflect next steps in a multi-step strategy (after identifying operation type), which could be deployed to solve fraction problems. For addition and subtraction problems, we anticipated that participants should first attend to denominators to assess whether they were the same or different to calculate common denominators as needed (Siegler et al., 2011). Thus, for addition and subtraction problems, participants who selected AOIs for either Denominator 1 or 2 received a score of 1 on that item, selection of any other non strategy-specific AOIs were scored as 0. For multiplication problems, a commonly employed strategy is to multiply across numerators first and denominators second (Siegler et al., 2011), thus participants who selected AOIs for either Numerator 1 or 2 received a score of 1 for that item; selection of any other non strategy-specific AOIs were scored as 0. For division problems, we anticipated participants would likely use the strategy of invert and multiply (Sidney et al., 2022) and thus the strategy-specific AOIs were operationalized as selection of Numerator 2 or Denominator 2 AOIs (scored as 1 for that item), and selection of any other non strategy-specific AOIs were scored as 0. For each participant, we then created an average strategy-specific AOI score that reflected the mean number of times participants selected a strategy-specific AOI (i.e., an AOI that was *aligned* with the operation type for that fraction arithmetic problem) for the eight critical trials. We originally anticipated examining strategy-specific AOI subscores for each operation category (addition/subtraction, multiplication, division); however, with the limited number of critical trials per operation type (n=2) we elected to focus our analysis of the self-report attention measure on participants' average strategy-specific AOI score.

Confidence Judgements After solving each problem, participants rated how confident they were in their answer on a scale from 0 to 100, where 0 indicated they were not confident in their answer, and 100 denoted complete confidence. We calculated average confidence overall, average confidence by operation type, and average confidence for the eight critical trials.

Numerical Stroop Task The numerical stroop task is a measure of EF, namely inhibitory control. In this task, participants were shown a series of single digit numeric dyads (Fitzsimmons et al., 2020b). Participants selected the physically larger number while ignoring the magnitude, or numerical value, of the numbers. The task included 112 trials: 32 congruent, 32 incongruent, and 48 neutral. For congruent trials, no conflicting information was given (i.e., the physically larger number was also a larger magnitude; 1 vs. 2). For incongruent trials, the dyads contained conflicting information (i.e., the physically larger number was of smaller magnitude; 1 vs. 2). For neutral trials, each dyad contained numbers of the same magnitude, only the physical size was altered (i.e., the same two numbers were presented with one number appearing physically larger than the other; 2 vs. 2).

We assessed participants' accuracy and reaction time (RT) on the Numerical Stroop Task. For each participant, we calculated average accuracy for each trial type (congruent, incongruent, neutral). We recorded the amount of time participants took to submit their response for each trial and calculated the average RT for each trial type. Analyses focus on accuracy and RT for incongruent trials (for correct trials only). Higher accuracy scores and faster RTs reflect greater EF (inhibitory control) proficiency.

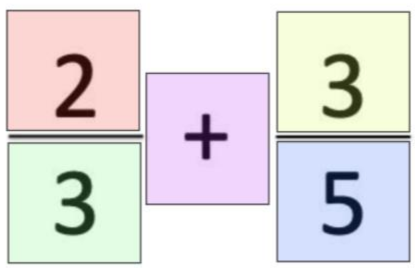

Figure 1: Schematic of AOIs (numerators, denominators, and operation) used for analysis of participants' mouse clicks in the self-report attention measure.

Results

Fraction Arithmetic Accuracy

Participants completed 24 arithmetic problems; average accuracy was 66% (*SD*=28%). Recall participants completed six problems per operation type (addition, subtraction, multiplication, division). In line with previous research with children and adults, we hypothesized that participants should exhibit the lowest accuracy on fraction division problems. To test this hypothesis we conducted a 4-way repeated measures ANOVA, with Greenhouse Geisser correction, on accuracy scores with operation type (addition, subtraction, multiplication, division) as the within-subject factor. There was a significant effect of operation type ($F(2.07, 805.83)=73.03$, $p<.001$, partial $\eta^2=.16$) on mean accuracy scores. Consistent with our hypothesis, pairwise comparisons indicated that participants did worse on division problems (*M*=52%, *SD*=42%) than on all other operation types: addition (*M*=72%, *SD*=30%), subtraction (*M*=75%, *SD*=28%), and multiplication (*M*=64%, *SD*=37%); all *ps*<.001. Participants were also more accurate on addition and subtraction problems than multiplication problems (both *ps*<.001), and on subtraction problems compared to addition problems (*p*=.006).

Correlations between Fraction Arithmetic Accuracy and Confidence Judgements Participants' mean confidence judgment score was 63.01 (*SD*=27.82). Across operation types, participants who reported greater confidence in their fraction arithmetic answers also tended to be more accurate on the fraction arithmetic problems (*r*=.73, *p*<.001). The same pattern of results was found *within* each operation type (all *rs* ≥ .55, all *ps* ≤ .001).

Self-Report Attention Measure, Fraction Arithmetic Accuracy, and Confidence Judgments

The following correlational analyses focus on the eight critical fraction arithmetic trials in which participants also reported the part of the problem they attended to first (i.e., selection of the operation, numerator, denominator AOIs). However, follow-up analyses were also conducted using all 24 fraction arithmetic trials to assess consistency and generalizability.

We hypothesized that participants would report attending to the Operation AOI across problem types, as the operation can signal to participants which multi-step strategy they should deploy to successfully solve each type of fraction arithmetic problem. Recall that for each participant the mean selection of the Operation AOI was calculated across the eight critical trials. Selection of the Operation AOI (*M*=29%, *SD*=36%) was not significantly correlated with participants' fraction arithmetic accuracy on critical trials (*M*=69%, *SD*=29%; *r*=.01, *p*=.92). This pattern also held when analyzing the correlation between participants' mean Operation AOI selection and their fraction arithmetic accuracy across all trials; selection of the Operation AOI was not significantly correlated with participants' total fraction arithmetic score (*r*=.03, *p*=.62). This surprising result could be an artifact of blocking problems by operation type, which may have inadvertently directed attention to other features of the problems. It is an open question as to how participants interpreted our prompt to click on the part of the problem they attended to first; we return to this point in the Discussion.

Next, we looked at the correlation between participants' mean selection of strategy-specific AOIs and their mean fraction arithmetic accuracy on the eight critical trials. Recall that for each participant, we calculated the mean selection of AOIs that were aligned with the operation type of each problem (i.e., selecting denominator AOIs for addition/subtraction problems, numerator AOIs for multiplication problems, and numerator 2/denominator 2 AOIs for division problems) across the eight critical trials. Mean selection of strategy-specific AOIs (*M*=39%, *SD* =27%) was significantly correlated with participants' average accuracy on the eight critical fraction arithmetic trials (*r*=.19, *p*<.001). This pattern of results was unchanged when substituting fraction arithmetic accuracy on all (24) trials in lieu of performance on the eight critical trials (*r* =.19, *p*< .001).

Correlation Between the Self-Report Attention Measure and Confidence Judgments

Participants' mean selection of strategy-specific AOIs on the eight critical trials was found to be positively correlated with their confidence judgments on those trials (*M*=64.82, *SD*=28.89; r = .11, p=.03). In other words, individuals who were more likely to report attending to AOIs that reflected strategies that were aligned to the operation type also reported greater confidence in their fraction arithmetic answers on those problems.

Inhibitory Control: Numerical Stroop Task

Stroop Performance A series of 3-way repeated measures ANOVAs, with Huynh-Feldt correction, with trial type (congruent, incongruent, neutral) as a within-subject factor revealed that participants' Stroop accuracy (F(1.54, 600.04)=65.47, p<.001, partial η^2=.14) and RT - for correct trials only (F(1.73, 672.01)=749.99, p<.001, partial η^2=.66) varied as a function of trial type. Overall, participants exhibited high levels of accuracy on the Numerical Stroop task. Pairwise comparisons indicated that participants were less accurate on incongruent trials (*M*=93%, *SD*=12%) compared to congruent (*M*=97%, *SD*=9%) and neutral trials (*M*=96%, *SD*=9%); both *ps*<.001. Similarly, participants' RTs (correct trials only) were significantly slower for incongruent trials (*M*=0.85s, *SD*=0.25s) as compared to congruent (*M*=0.71s, *SD*=0.25s) and neutral trials (*M*=0.74s, *SD*=.25s); both *ps*<.001).[1]

Correlation between Inhibitory Control and Math Performance We examined the association between participants' inhibitory control indexed by their RT on incongruent trials (correct trials only) and their performance on the fraction arithmetic problems. Participants with better inhibitory control (i.e., shorter RTs) were also more accurate on the fraction-arithmetic problems (r = -.18, p<.001).[1]

Correlation between Inhibitory Control and Self-Report Attention Measure Next, we assessed whether participants with stronger inhibitory control (based on RT for incongruent trials - correct trials only) also tended to report attending to strategy-relevant AOIs when solving fraction arithmetic problems. Participants' mean selection of strategy-specific AOIs was negatively correlated with their RTs on incongruent trials, such that individuals with better inhibitory control (i.e. shorter RTs) were more likely to attend to the appropriate strategy-specific AOIs (r = -.15, p = .006)[1].

Discussion

The present study provides several insights into relations among fraction performance, problem-solving strategies, and executive functions. Using Heat Maps in Qualtrics to index participants' attention to strategy-relevant AOIs, we found initial correlational evidence supporting the finding that individuals who report attending *first* to strategy-relevant fraction components tended to be more accurate on fraction arithmetic problems. Fraction division problems were more difficult for participants, as has been shown in previous studies (Sidney et al., 2019; Siegler et al., 2011). Future research could include more items per fraction-arithmetic operation and explore whether the relation between selection of strategy-specific AOIs and accuracy holds for each of the four operations.

One surprising finding was that participants did not click on the Operation AOI with as much regularity as anticipated. This likely occurred because problems were blocked by operation type so participants could provide a predictive judgment about how many problems they would correctly solve as part of the larger study design. Future work could interleave problems of different operation types, and in doing so, participants may be more likely to report attending to the Operation AOI first to help them plan the necessary steps to accurately solve the problem.

The present study also highlights the potential role of inhibitory control on adults' fraction performance. Consistent with prior work, individuals with better inhibitory control also tended to obtain higher accuracy scores. Additionally, they were more likely to report attending to strategy-relevant AOIs. In the present study, we utilized a domain-specific measure of inhibitory control, a numerical stroop task. Some prior research has found a stronger correlation between mathematics achievement and inhibition tasks that involve numerical information vs. tasks that require inhibition of non-numerical information (see Gilmore et al., 2015). In future research, it will be important to incorporate both domain-specific and domain-general measures of inhibitory control to investigate possible domain-specific effects in the context of fraction arithmetic.

This study provides initial support that Heat Maps can be used as a measure of adults' self-reported attention and index of dynamic strategy variability (Alibali & Sidney, 2015; Fitzsimmons et al., 2020b), making Heat Maps a beneficial tool for remote data collection. However, some limitations should be addressed in future work. First, participants self-reported which parts of the equations captured their attention first. The validity of these reports is unknown. Previous studies from the strategy-report literature have asked children and adults to describe how they solved fraction problems,

[1] Note that when the RT analyses only include responses that are made within 2s, the pattern of results is unchanged: the 3-way repeated measures ANOVA, with Huynh-Feldt correction, with trial type (congruent, incongruent, neutral) as a within-subject factor again revealed that participants' Stroop RT for correct trials only (F(1.72, 666.57)=764.61, p<.001, partial η^2=.66) varied as a function of trial type. Participants' RTs were significantly slower for incongruent trials compared to congruent and neutral trials (both *ps*<.001). The negative correlation between inhibitory control (RT) and accuracy on the fraction arithmetic problems remained significant (r=-.17, p=.001) as did the correlation between inhibitory control (RT) and selection of the strategy specific AOIs (r=-.13, p=.02).

which did not necessarily result in participants describing aspects of the problems they attended to and in which order. However, future research can utilize eye-tracking technology to better assess the extent to which participants' self-reported attention aligns with more objective and implicit measures (see preliminary results in Wall et al., 2015).

It is also necessary in future research to consider how characteristics of the stimuli as well as experience may impact attention allocation patterns, such as the extent to which the location of the operation symbol at the middle of the screen may capture participants' attention (much like an orientation trial used in other cognitive tasks). Additionally, participants who have orthographies that are oriented left-to-right, like our English-speaking participants, may be more likely to attend to Numerator 1 (top left) given the tendency to process fraction arithmetic problems from left-to-right (see Opfer et al., 2010 for discussion of spatial-numeric associations). Third, in the current study, we asked participants to report the first place that they attended to by making a single mouse click. In future research, it will be beneficial to capture participants' problem-solving steps sequentially. This will be especially helpful as we extend our methodology to children and attempt to establish at which step in the problem-solving procedure children's strategies went awry. Thus, this line of work has the potential to inform interventions and instructional strategies to yield improvements in math achievement.

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