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RESEARCH ARTICLE

Exploring the Relationship Between Response Time, Studying STEM and Substitution Bias

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As ‘cognitive misers’, humans often fall prey to substitution bias, whereby a difficult problem is mentally substituted for an easier one. A quasi-experimental study was conducted to explore individual differences in vulnerability to substitution bias. Results demonstrate that studying Science, Technology, Engineering and Mathematics (STEM) subjects, and spending more time on the problem correlates to a reduced likelihood of substitution bias. However, there was no interaction between studying STEM and time spent solving the problem on the likelihood of substitution bias. We discuss the possibility that education-related increases in mathematical or logical thinking skills engage the effortful and slow aspects of dual-process systems of human cognition.

Keywords: substitution bias, attribute substitution, dual-process theories, STEM

Substitution bias, or attribute substitution, refers to mentally switching an effortful problem for an easier one (Kahneman & Frederick, 2002). Substitution bias arises from employing heuristics - cognitively undemanding “rules of thumb” applied by an automatic, fast-thinking aspect of the mind, as opposed to effortful, controlled, slow-thinking (Evans, 2008). Dual-system thinking allows rapid responses to problems using limited cognitive resources, but heuristic-based reasoning is often wrong (Evans, 2010). People generally do not recognise substitution has occurred, making them “happy fools” (Kahneman & Frederick, 2005; Thompson, 2009; Toplak, West, & Stanovich, 2011). However, recent research found that people report lower confidence in their answer after falling prey to substitution bias, demonstrating that, contrary to the previous reasoning, people have some small awareness that substitution bias has occurred, described as “minimal awareness” (De Neys, Rossi, & Houdé, 2013).

Dual-process theories emerged from the theory of automaticity, whereby humans can carry out certain tasks without occupying the conscious mind (Servant, Cassey, Woodman & Logan, 2018). These theories taxonomise human thought processes into System 1 and System 2 (Kahneman, 2011). System 1 is automatic, without conscious control, uses minimal cognitive resources such as working memory and attention, and often relies on heuristics, resulting in varying degrees of accuracy (Banks, Gamblin, & Hutchinson, 2020). With substitution bias, it is System 1 thinking that replaces aspects of the problem with simpler, more easily solved aspects (Andersson et al., 2020). Alternatively, System 2 is intentional, with conscious control over starting and stopping, and an occupation of mental resources. Dual-process theories differ in the interrelationship between System 1 and System 2, and empirical evidence suggests processes are not solely one system, but at times a combination of both (Melnikoff & Bargh, 2018).

Substitution bias is commonly measured using the Cognitive Reflection Test (CRT) which comprises three problems (Frederick, 2005). These problems are designed

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to elicit an intuitive, fast response that runs counter to the correct response. Arriving at the correct response is thought to require the deliberative and effortful aspects of system 2 thinking. The classic bat and ball problem is one of the CRT problems. The problem is stated as follows: “A bat and ball together cost $1.10. The bat costs $1 more than the ball. How much does the ball cost?” The intuitive answer values the ball at 10 cents, but a review shows that if the bat costs $1 more, then its value would be $1.10, making the total $1.20. Therefore, the correct answer is 5 cents (Bago & De Neys, 2019).

De Neys et al. (2013) found that only 21% of their 248 participants correctly solved the problem above and therefore engaged System 2 thinking instead of System 1. Their results also demonstrated a drop in answer confidence following completion of the problem compared to an easier isomorphic control, suggesting that, while participants were not so aware of their substitution bias to actively prevent it, they were aware that something was not right with their answer, discussed as minimal awareness of substitution bias.

Time spent answering the question may also affect such cognitive biases. If System 1 is fast and automatic, and System 2 is slow and conscious, then the amount of time spent on a problem is likely to be significant in determining if a problem-solver falls prey to substitution bias. Past research has shown that correct reasoners take longer to achieve the right answer (Alós-Ferrer & Hügelschäfer, 2016; Stupple, Gale, & Richmond, 2013; Travers, Rolison, & Feeney 2016).

It is hypothesised that education may be related to substitution bias. Given that mathematical ability, numerical confidence, and mathematical anxiety may be important aspects of performing well on the CRT (Primi, Donati, Chiesi, & Morsanyi, 2018) and that less biased reasoners have stronger critical (Maynes, 2015) and logical thinking skills (Haselton, Nettle, & Murray, 2015). These factors are relevant aspects of studying Science, Technology, Engineering & Mathematics (STEM) subjects, which provide enhanced training in logic, critical thinking, and familiarity with numerical problems (Smith & White, 2019). However, those who possess stronger logical thinking skills may be more attracted to studying STEM subjects, for example, LeFevre, Kulak, and Heymans (1992) showed that those with mathematics anxiety/lower arithmetic skills tend to study non-STEM subjects at university. This paper aims to determine if those who study a STEM subject have a reduced vulnerability to substitution bias. Previous research on biased thinking in STEM has focused mainly on attitudes to women in STEM (e.g., Jackson, Hillard, & Schneider, 2014; Robnett, 2016), and there appears to be no current work on the influence of STEM education on substitution bias.

Methods

Here, we replicated and extended the work of De Neys et al. (2013). Similar to De Neys et al. (2013), we deployed a questionnaire that consisted of two problems: 1) the bat and ball problem which gives rise to substitution bias, and 2) an appropriate control version that does not. The surface similarity of the two problems was minimised by changing the superficial item content, and the question presentation was counterbalanced to control for order effects. Participants were also asked to rate their confidence that their answer was correct immediately following each question. We extended this work with individuals who had or had not studied a STEM subject in university, inferring that STEM students will be, on the whole, more accurate. We also measured time spent answering the problems, hypothesizing that STEM participants might spend longer answering the question, demonstrating more effortful reasoning, and therefore avoiding substitution bias.

Participants

The experiment received ethical approval through the authors’ institutional proportionate review process. 169 individuals were recruited through email and social media. 37 participants were removed for not completing the full experiment. The remaining sample (N = 132, 55.3% female), was normally distributed in age between 18-71 years ($Mage$ = 34, SD = 13.31). Most participants were university-educated (93.2%), had studied a STEM subject if they were university educated (59%) and spoke English as a first language (73.5%).

Materials

This study directly replicated the within-subjects design of De Neys et al. (2013) using Qualtrics. Participants viewed two questions, 1) a bias-invoking problem, and 2) a control problem, with the questions from De Neys et al. (2013) adapted for cultural validity. To avoid any order effects, the questions (control versus bias-invoking), and the superficial item content and numerical values used (‘pencil and eraser at £2.90 and £2’ versus ‘magazine and banana at £1.10 and £1’), were cross-matched. Thus, four experimental conditions were formed. The participants were randomly assigned to conditions by the Qualtrics software.

The bias-invoking question read: "A pencil and an eraser/magazine and a banana cost £1.10/£2.90 in total. The pencil/magazine costs £1/£2 more than the eraser/banana. How much does the eraser/banana cost?" Participants were asked to give their answers in pence to avoid data validation errors caused by decimal points. Participants were scored as 'correct' if they answered £0.05/£0.45, 'biased' if they answered £0.10/£0.90, and 'incorrect' if they answered with any other number.

The control question read: "A pencil and an eraser/magazine and a banana cost £1.10/£2.90 in total. The pencil/magazine costs £1/£2. How much does the eraser/banana cost?" Participants were scored as 'correct' if they answered £0.10/£0.90, or 'incorrect' if they answered with any other number.

After each question, participants were asked to self-report their confidence in their answer in percentage format, with 100% representing total confidence.

Procedure

After providing consent, participants solved the two problems. Response time and self-rated confidence in the answer were recorded for both problems. Participants then answered demographic questions including gender, age, native language, and university study (Currently Attending, Previously Attended, Never Attended). If they attended university, they were also asked if they studied a STEM subject (Yes/No) and which subject (free text response). A debriefing and final consent concluded the experiment.

Analysis

Baseline analyses were first carried out to ensure no ordering effects between the four experimental conditions. Biased reasoners were defined as those who gave the biased answer to the bias-invoking question, non-biased reasoners were defined as those who gave the correct answer to the bias-invoking question, and incorrect reasoners were defined as those who gave an incorrect, but non-biased answer in the bias-invoking question. Following De Neys et al. (2013), analyses comprised of a between-subject ANOVA comparing accuracy levels on each question (bias-invoking and control). Within-subjects ANOVAs also compared confidence levels on each question type for both biased and non-biased reasoners. Participants who gave incorrect answers to the control problem, or incorrect reasoners on the bias-invoking question, were dropped from further analysis. The chi-squared analysis determined if there was an association between studying a STEM subject and getting the correct answer on the bias-invoking question. Two one-way within-subjects ANOVA then examined if there was a relationship between studying STEM and confidence ratings, and between studying STEM and response times. Finally, binomial logistic regression was used to determine which factors predict answering accuracy on the bias-invoking question.

Results

Baseline analyses indicated that the four experimental conditions were equivalent in terms of age ($F(3, 128) = 0.86$, $p = .464$, $\eta_p^2 = .02$), gender ($\chi^2(3, N = 132) = 3.72$, $p = .288$, $\varphi_c = .17$), English language ($\chi^2(3, N = 132) = 1.16$, $p = .763$, $\varphi_c = .09$), university attendance ($\chi^2(6, N = 132) = 9.99$, $p = .125$, $\varphi_c = .26$), or if a STEM subject was studied ($\chi^2(3, N = 123) = 1.12$, $p = .772$, $\varphi_c = .10$). There was no significant association between condition and answering accuracy for the control question ($\chi^2(3, N = 132) = 1.85$, $p = .605$, $\varphi_c = .12$), or the bias-invoking question ($\chi^2(6, N = 132) = 5.22$, $p = .516$, $\varphi_c = .20$), nor between conditions and time spent answering the control question ($F(3, 128) = 2.58$, $p = .056$, $\eta_p^2 = .06$) or the bias-invoking question ($F(3, 128) = .16$, $p = .913$, $\eta_p^2 = .004$). Similarly, no association was found between conditions and confidence ratings on the control question ($F(3, 128) = 1.19$, $p = .318$, $\eta_p^2 = .03$) or the bias-invoking question ($F(3, 128) = 1.23$, $p = .302$, $\eta_p^2 = .03$). Overall, there were no order effects and four experimental conditions were determined to be equivalent for the control question and the standard question. All control questions were grouped together as were all standard questions for further analysis.

A between-subjects ANOVA showed a statistically significant main effect of the question type on accuracy ($F(1,131) = 123.51$, $p < .001$, $\eta_p^2 = .49$). Participants most often got the control question correct and then the bias-invoking question incorrect (51%), followed by getting both correct (46%). Participants spent significantly (see later results from the logistic regression) more time answering the bias-invoking question ($M = 58.51$ seconds) and were less confident in the answer ($M = 95.94\%$) than with the control question ($M = 26.15$ second, $M = 97.40\%$) (Table 1). The six participants who were incorrect on the control problem, or incorrect reasoners on the bias-invoking question, were dropped from further analysis. Subsequently, question accuracy was recoded as 0 = biased, 1 = correct for the bias-invoking question.

Table 1. Time and confidence results for participants by question type.

Variables	Bias-Invoking Question		Control Question	
	M	SD	M	SD
Time Spent Answering (seconds)	58.51	69.28	26.15	32.97
Confidence in Answer (%)	95.94	10.84	97.40	11.03

Note: N = 132.

Table 2. Specification of Model I.

Predictor	β (SE)	95% CI for Odds Ratio			p
		Lower	Odds Ratio	Upper	
Intercept	-4.670 (2.433)	7.54 x 10-5	.009	1.104	.055.
Time Spent on Bias-Invoking Question (seconds)	0.032 (.008)	1.016	1.033	1.049	<.001***
Confidence in Answer to Bias-Invoking Question (%)	0.021 (.024)	.975	1.021	1.070	.376
Gender	0.832 (.466)	.921	2.297	5.731	.075.
Age (Years)	-0.015 (.022)	.944	.985	1.028	.499
First Language	0.466 (.588)	.534	1.593	4.757	.404
Studied a STEM Subject at University	1.488 (.512)	1.625	4.428	12.068	.004**

Note: R2 (Cox-Snell) = 0.321, AIC = 131.681, Model χ2 (6) = 45.766, p < .001
*. p < .1, * p < .05, ** p < .01, *** p < .001*

Within-subjects ANOVA showed a statistically significant main effect of question type on confidence for both biased reasoners ($F(1,125) = 9434.37$, $p < .001$, $\eta_p^2 = .99$) and non-biased reasoners ($F(1,125) = 30584.73$, $p < .001$, $\eta_p^2 = .10$). Regardless of whether participants got the bias-invoking question right or wrong, they were always more confident in their answer to the control question than the bias-invoking question.

Following this, participants who had not studied at university were excluded (*n* = 8). There was a statistically significant association between studying STEM and accuracy in the bias-invoking question ($\chi^2(1, N = 118) = 12.48, p < .001$). Participants were more likely to answer the bias-invoking question correctly if they had studied a STEM subject (78.69%) compared to those who had not studied a STEM subject (21.31%).

A one-way within-subjects ANOVA showed no statistically significant main effect of studying STEM on confidence for either the bias-invoking question ($F(1, 55) = 2.12, p = .151$) or the control question ($F(1, 53) = 0.31, p = .581$). A further one-way within-subjects ANOVA showed there was also no statistically significant main effect of studying STEM on response time for either the bias-invoking question ($F(1, 108) = .41, p = .552$) or the control question ($F(1, 84) = 0.19, p = .666$).

A binomial logistic regression model tested the relationship between bias likelihood and participant characteristics. Model I was estimated using forced entry of all collected predictors (Table 2) and was a statistically significant model ($\chi2\ (6) = 45.77, p < .001$). Participants were 4.43 times (95% CI = [1.63, 12.07]) more likely to be correct if they studied a STEM subject ($p = .004$). Participants were also 1.03 times (95% CI = [1.02, 1.05]) more likely to be correct if they spent more time on the question ($p < .001$). However, R^2_{CS} indicated that only 32% of the variance in biased reasoning was explained by the predictor variables.

A more parsimonious Model II was estimated using the significant predictors from Model I (Table 3). This was also a statistically significant model ($\chi2\ (2) = 40.84, p < .001$). Again, being free from bias was positively related to studying a STEM subject (*OR* = 5.35, 95% CI = [2.05, 13.92], $p < .001$) and spending more time on the question (*OR* = 1.03, 95% CI = [1.01, 1.04], $p < .001$). R^2_{CS} indicated that 29% of the variance in biased reasoning could be explained by the predictor variables, suggesting that in Model 1, confidence, gender, age and first language explained only three percent of the variance in biased reasoning. Model II had a better goodness-of-fit, indicating that time spent and STEM were key predictors of the likelihood of substitution bias. Respectively, they contributed 20% and 10% of the variance. Thus, time spent appeared to be a slightly stronger predictor of the likelihood of substitution bias. Including an interaction term in Model II revealed no interaction effect between time spent and studying STEM ($\beta = 0.024, p = .106$).

Discussion

This paper investigated the relationship between studying a STEM subject, time spent on answering a problem and their relationship to substitution bias. Participants were significantly less confident in answering the bias-invoking question, compared to the control, regardless of answering accuracy. Thus, there was no

Table 3. Specification of Model II.

		95% CI for Odds Ratio			
Predictor	β (SE)	Lower	Odds Ratio	Upper	p
Intercept	-2.359 (.536)	.033	.095	.270	<.001***
Time Spent on Bias-Invoking Question (seconds)	0.028 (.007)	1.014	1.028	1.043	<.001***
Studied a STEM Subject at University	1.676 (.488)	2.054	5.347	13.916	<.001***

Note: R2 (Cox-Snell) = 0.293, AIC = 128.602, Model χ2 (2) = 40.845, p < .001
*. p < .1, * p < .05, ** p < .01, *** p < .001*

evidence for minimal awareness of substitution bias as measured by a confidence rating (De Neys et al., 2013). These results suggested that the bias-invoking question was more cognitively demanding than the control question for all participants. Similar to previous research (Bourgeois-Gironde & Vanderhenst, 2009; De Neys et al., 2013; Frederick, 2005), it was found that participants generally committed the substitution bias error, but unlike previous studies, the proportion of participants who gave the correct answer on the bias-invoking question was much higher (46% compared to approximately 20%).

It is proposed that the difference in accurate reasoning may be accounted for by time spent answering the question and having studied a STEM subject at university. Those who studied STEM subjects tended to have a higher answering accuracy on the bias-invoking question than those who studied non-STEM subjects. Furthermore, having studied a STEM subject was a statistically significant predictor of protection against substitution bias.

Taking the STEM and non-STEM groups separately, the proportions who committed the substitution bias error seemed to reflect previous research. Frederick (2005) and Kahneman & Frederick, (2007) showed that students from universities with a stronger reputation for STEM subjects performed better on the bat-and-ball problem than those from universities with a lower reputation for these subjects. It has been shown that studying a STEM subject provides enhanced training in logic, critical thinking, familiarity with numerical problems and mathematical ability (Smith & White, 2019) and that critical thinking is correlated with avoiding bias (West, Toplak, & Stanovich, 2008). The CRT can predict rational thinking (Toplak, West, & Stanovich, 2014), so it is possible here that the correlation between the first item of the CRT and STEM education indicates that STEM may enhance rational thinking, or certainly attract those more prone to rational thinking as a career choice.

As well as indicating enhanced mathematical and reasoning abilities, studying a STEM subject may also be linked to positive perceptions of mathematical ability (Primi et al., 2018) and inversely related to mathematics anxiety (Morsanyi, Busdraghi, & Primi, 2014). This has been related to better attentional control and the ability to inhibit the easily available heuristic response in people who do not have mathematics anxiety. For example, LeFevre et al. (1992) showed that those with lower arithmetic skills tended to study non-STEM subjects at university. It was also found that time spent answering the bias-invoking question, rather than having studied a STEM subject, was the strongest predictor of getting the bias-invoking question correct. This statistically significant result predicted producing the correct answer, coinciding with previous similar research (Alós-Ferrer & Hügelschäfer, 2016; Stupple et al., 2013; Travers et al., 2016).

There was no interaction effect between time spent answering the bias-invoking question and having studied STEM, suggesting that those who got the answer correct did not necessarily spend more time answering simply because of their STEM status.

Overall, these results suggest that there is a correlation between studying a STEM subject at university and an increased likelihood that the effortful aspects of System 2 thinking will be engaged and correctly executed. Effortful processing requires a willingness to engage cognitive resources to solve problems which may increase concentration and decrease the likelihood of falling prey to substitution bias (Westbrook & Braver, 2015). Those who spent longer answering were also more likely to be correct. Taking more time to answer has been strongly linked to engaging in System 2 type thinking (Alós-Ferrer & Hügelschäfer, 2016; Stupple et al., 2013; Travers et al., 2016). However, given that there was no significant interaction effect between STEM and time, it is proposed that effortfulness and slowness are separate aspects of System 2 which are independently engaged. The desire to spend more time on a problem, given that it does not arise concurrently with studying STEM, could be linked with other underlying individual differences related to thinking dispositions, intellectual style (Kozhevnikov, Evans, & Kosslyn, 2014), or the personality trait of reflectivity (Dickman & Meyer, 1988). It also indicates that it may be possible to target and train the effortful aspects of System 2 to reduce vulnerability to substitution bias. However, the correlational nature of the study means that it remains undetermined whether studying STEM causes an increase in the probability that the correct answer will be arrived at or whether those who study STEM already possess underlying traits that make this more likely.

The main limitation of this study was its quasi-experimental and correlational nature. Since the sample was chosen from a naturally occurring population randomisation was achieved through the counterbalancing of experimental conditions. However, due to its exploratory nature, causality could not be determined. Additional training in mathematics and reasoning through studying STEM may not account for the differences observed, rather it may be that those with stronger logical reasoning skills are drawn to studying STEM subjects to begin with (LeFevre et al., 1992). Nonetheless, this study does highlight that differences exist between those who study STEM and non-STEM subjects, and this may warrant further investigation to ascertain if STEM training is a contributing factor to protection against substitution bias.

The second potential limitation was the participants' self-identification with studying STEM subjects. Subjects studied at third level were recorded for simple verification, yet what constitutes a STEM subject is debated. For example, many students do not consider psychology courses at third level to be STEM subjects (Amsel, Ashley, Baird, & Johnston, 2014). This was highlighted in the present sample of 14 participants who indicated they studied psychology. Of this group, seven said psychology was a non-STEM subject. Here, for feasibility, it was decided to use participants' self-reported STEM classifications which may have lowered the validity of STEM as a construct, since it may have included students who did not study STEM as considered by certain perspectives (National Academy of Science [NAS], 2006; Bray, 2010). In future, a more explicit definition of STEM should be adopted with complete researcher verification post-survey completion.

Future research could aim to determine if training in STEM subjects may be causal in reducing substitution bias as distinct from factors that draw students to study these subjects (thinking dispositions, intellectual styles, etc.). This could be done by incorporating a longitudinal design into the study, measuring students' responses to CRT style questions at the start of their third level studies and again at the end of their studies. Measuring moderating factors such as Intelligence Quotient and Grade Point Average would also help isolate the influence of their advanced education and training. Finally, future research could employ a more accurate way of classifying respondents as STEM or non-STEM trained, to better understand the underlying factors of studying STEM and their contribution to avoiding substitution bias.

In conclusion, to the best of the authors' knowledge, this paper is one of only a few to examine the relationship between STEM education and limiting cognitive bias, and the only one to look specifically at the relationship between STEM education and substitution bias. Studying a STEM subject and spending longer answering versions of the bat and ball problem were both found to be significant predictors of answering accuracy suggesting that to avoid substitution bias one should aim to think longer and harder about a question. However, given that no interaction was found between STEM and time, the results indicate that System 2 thinking may consist of independent slow and effortful aspects. Future work should consider individual differences in education when exploring cognitive biases to further determine whether specific training in STEM reduces the likelihood of falling prey to substitution bias.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

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