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Rethinking the role of automaticity in cognitive control

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Behaviour that is assumed to be guided by strategy can, in fact, be based on the implicit learning of regularities in the environment. We demonstrate this point in the context of a Stroop experiment. It has been shown previously that performance on this measure of cognitive control varies as a function of the relative proportions of congruent and incongruent trials in a block. Here we provide evidence that this modulation of performance is largely based on implicit, rather than explicit, knowledge of these proportions. This result has important implications for our understanding of cognitive control.

Keywords: Cognitive control; Strategy; Stroop; Proportion effects; Awareness.

The last few decades have seen an explosion in research on the cognitive control of action and the regulation of behaviour. The literature in this area can be divided into two broad categories. The bulk of it focuses on deliberate cognitive control and implicates the prefrontal cortex (Braver, Cohen, & Barch, 2002; Miller & Cohen, 2001). Most of the data in this area are based on paradigms in which rules and strategies are argued to regulate behaviour (Bunge & Wallis, 2007). The second focuses on adaptive or implicit control (Blais, Robidoux, Risko, & Besner, 2007; Verguts & Notebaert, 2008). Much of the information in this area is based on paradigms in which environmental cues regulate behaviour (see Blais, 2010, for an extensive review).

The purpose of this paper is to make a simple point: It is possible to infer that individuals are behaving strategically when in fact their behaviour is guided implicitly by regularities in their environment. To demonstrate this point, we focus on an effect that is generally agreed to be the result of strategic behaviour—the finding that performance on the Stroop task is affected by the proportion of congruent trials in a block (e.g., Logan & Zbrodoff, 1979; Logan, Zbrodoff, & Williamson, 1984). We argue below that because participants have little awareness of the composition of the experiment, it is difficult to envision how they could possibly generate a deliberate strategy to compensate for the composition of trials.

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A process is generally considered automatic if it is stimulus driven, occurs without intent, is capacity free (on some accounts), and cannot be derailed or interrupted. Controlled processes, simply put, are those that are not automatic (see Posner & Snyder, 1975; Shiffrin & Schneider, 1977, for more thorough criteria). The general failure to find universally automatic cognitive processes has resulted in a shift toward placing processes along a continuum of automaticity, whereby one process is more or less automatic than another process (e.g., Cohen, Dunbar, & McClelland, 1990; MacLeod & Dunbar, 1988).

Performance on the Stroop task is often used as evidence that word recognition is more automatic than colour naming. In this task, the participant is asked to name the print colour of a colour word; if the word GREEN printed in blue is presented, the correct response is "blue". Despite the participant's best effort to ignore the word, it will influence behaviour such that it is faster to name the colour when the word and colour refer to the same concept (a congruent trial) than when they refer to different concepts (an incongruent trial). This difference in response time (RT) is the prototypical Stroop effect. However, if the participant is asked to respond to the word, the colour has little impact on performance (i.e., the reverse Stroop effect is considerably smaller, or even absent, see Blais & Besner, 2006).

The reliability with which the Stroop effect is obtained demonstrates that it is extremely difficult to prevent the word from being processed. However, the magnitude of the Stroop effect is affected by the relative number of congruent trials in a list, such that the Stroop effect is larger when the proportion of congruent trials is high than when the proportion of congruent trials is low (e.g., Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Logan et al., 1984). Specifically, RTs to congruent trials are relatively faster when the proportion of congruent trials is high than when it is low. Conversely, RTs to incongruent trials are relatively slower when the proportion of congruent trials is high than when it is low. This effect is referred to below as the *proportion by congruency interaction*. The most common interpretation of this effect is that participants detect and use the fact that the colour and the word dimensions are correlated to control how much they allow the word to influence performance (e.g., Cheesman & Merikle, 1986; Lindsay & Jacoby, 1994; Lowe & Mitterer, 1982). As a case in point, Lowe and Mitterer concluded that their results "demonstrate the strategic modulation of selective attention" (Lowe & Mitterer, 1982, p. 698). Similarly, in an assessment of probability effects, Cheesman and Merikle conclude: "Probability effects...have been investigated using a variety of tasks, and the results of these studies generally have been interpreted to indicate that observers adopt voluntary processing strategies which utilize the predictive information provided by the primes" (Cheesman & Merikle, 1986, p. 347). When the correlation (hereafter, contingency) is high, participants increase their use of the word leading to faster RTs on congruent trials but much slower RTs on incongruent trials. When the contingency is low, participants suppress their use of the word, leading to relatively slower RTs on congruent trials but relatively faster RTs on incongruent trials.

By this account, it is difficult to envision how such selection could occur in the absence of knowledge of the proportion of congruent trials. Otherwise, participants would be unable to switch between reading the word because it matches the correct response in one context and ignoring the word because it rarely matches the correct response in another context. Thus, to test whether awareness of this proportion modulates the proportion congruent by congruency interaction, it is important to know whether participants are, in fact, aware of the proportion of congruent trials.

Therefore, we sought to test the hypothesis that awareness of the proportion of congruent trials is necessary for the proportion congruent by congruency interaction. Merikle and colleagues (Cheesman & Merikle, 1986; Reingold & Merikle, 1988) have argued that the only way to assess the contents of participants' subjective experience is to ask them about it. Furthermore, we know that participants' guesses can be based on information from both conscious and unconscious sources. Work in the field of implicit memory suggests that the best way to assess whether a memory is also based on conscious information is to have participants rate the confidence of their memory. If their confidence is low, that is taken to indicate that the memory is implicit and free of declarative (conscious) influence.

With these concepts in mind, we conducted a simple experiment in which we presented participants with a number of short blocks of trials in which the proportion of congruent trials was varied (Experiment 1). The novel part of this experiment is that after each block of trials, participants were asked to guess whether there were more congruent trials or incongruent trials, rate how confident they were about this choice, and provide a numerical estimate of the actual proportion of congruent trials. By comparing the size of the Stroop effect when participants reported that they were sure of the proportion of congruent trials to the size of this effect when participants reported that they were unsure of the proportion of congruent trials, we could assess whether awareness of the proportion of congruent trials is critical for, or modulates, the proportion congruent by congruency interaction. To assess whether our results were influenced by these probe questions, we also tested an additional group of participants who did not receive these questions (Experiment 2).

EXPERIMENT 1

Method

Participants

A total of 9 undergraduates (2 females) from the University of California, Berkeley, served as participants. Participants were paid at a rate of $20 per hour ($200 maximum) for the 8.5–10-hour experiment. Informed consent was acquired from all participants in accordance with the Institutional Review Board at the University of California, Berkeley.

Task

Participants performed 190 blocks[1] of trials of the Stroop task, each of which included 12 practice trials in which they named the colour of a colour patch followed by 100 experimental Stroop trials and took between 2–3 min to complete. Participants did this over a period of 2 to 4 weeks pending mutual availability of the participant and a research assistant (M.B.H. or J.V.G.) completing 20–40 blocks each day at their own pace. The 190 blocks varied in the proportion of congruent and incongruent trials, ranging from 5% to 95% congruent trials in increments of 5%; participants performed 10 blocks at each of these 19 proportions. Each participant received the same randomly ordered sequence of blocks.

The stimuli were presented against a black background. Practice trials began with a fixation marker for 250 ms (the number 12, which counted down to 1 with each subsequent trial). A colour patch then appeared and remained on the screen until the participant made a vocal response to its colour. The response was followed by a 250-ms blank screen. Following the 12 practice trials, there was a 750-ms blank screen, after which the 100 experimental trials were presented. On the experimental trials, the fixation marker consisted of a crosshair, and the target was 1 of the 16 combinations of the words (red, blue, green, and yellow) paired with those same colours. Whenever the program required a congruent trial, one was sampled randomly with replacement from the 4 possible congruent stimuli. Whenever the program required an incongruent trial, one was sampled randomly with replacement from the 12 possible incongruent stimuli.

In the bottom left corner of the display, approximately 23° from fixation, the trial number was presented on the screen in dark grey (RGB: 100,100,100). This allowed the experimenter sit behind the participants and passively score trials on which a word other than the colour (an error)

[1] A total of 5 participants completed 189 sessions; 1 missed a 25% block, 2 missed a 50% block, and 2 missed a 95% block.

was said, or the microphone failed to fire, fired too early, or the participant coughed (a mistrial).

Participants in Experiment 1 were asked three questions pertaining to their perception of the number of congruent trials following each block:

1. Select the best option:
   a. More congruent trials than incongruent trials
   b. More incongruent trials than congruent trials
2. With respect to the previous question:
   a. That's a guess
   b. I'm sure
3. In total there were 100 colour-word combinations. How many were congruent?

Results

Correct RTs longer than 2,000 ms (outliers) or shorter than 200 ms (anticipatory) were excluded, as were RTs that were more than 2.5 standard deviations away from the mean within each cell (subject by block by congruency). The mean correct RT data and percentage error data for each group are presented in Figure 1 as a function of congruency and proportion.

Response times and errors were modelled separately at the block level[2] for each participant with a full factorial regression analysis with congruency and proportion as factors. The standardized parameter values for each participant were then tested for deviance from zero using a one-sample t test. For brevity, these estimates are given as 95% confidence intervals in the format ($x \leq \beta \leq y$); the parameter is statistically significant if this range does not include zero.

This analysis confirms the patterns evident in Figure 1. The proportion effect was significant in RTs ($-.178 \leq \beta \leq -.089$) and errors ($.034 \leq \beta \leq .220$). The congruency effect was significant in RTs ($.422 \leq \beta \leq .638$) and errors ($.109 \leq \beta \leq .397$). And critically, the proportion by congruency interaction was significant in RTs ($.208 \leq \beta \leq .319$) and errors ($.064 \leq \beta \leq .251$). Thus, consistent with prior research, we found that the size of the Stroop effect increases as a function of the number of congruent trials in a block. Furthermore, this effect appears to be entirely linear (see the solid circles in Figure 5).

To assess whether awareness of the actual proportion plays a role in the size of the Stroop effect, we analysed the results of the probe questions. Not surprisingly, Figure 2B shows that participants were considerably better at estimating the actual proportion of congruent trials when they reported that they were sure about the proportion than when they were guessing (slope = .82 when aware vs. .21 when unaware, $p < .05$, where a slope of 1 would indicate perfect performance). Also to be expected, the closer the actual proportion of congruent trials was to 50%, the less confident participants were regarding whether there were more congruent or incongruent trials in the block (see Figure 2A). Overall, participants were sure of the proportion of congruent trials on 65.2 ± 16.2% of the blocks (range of 41.1 to 85.2).

To test whether being sure about the number of congruent trials had an effect on Stroop performance, we conducted another regression analysis that included confidence as a factor and found that none of the interaction terms involving confidence or the main effect was significant (in RTs, ps $> .19$, in errors, ps $> .12$). Planned uncorrected follow-up t tests comparing the size of the Stroop effect at each proportion yielded a difference in the 30% block, $t = 2.57$, $p = .033$, and marginal effects in the 40% block, $t = 1.95$, $p = .087$, and the 90% block, $t = 2.04$, $p = .076$. All other tests were nonsignificant (ps $> .18$). The results of these t tests can be seen graphically by the unsure−sure line in Figure 2C. Note that the error bars represent 95% confidence intervals; if the error bar includes the 0 line, there is not a significant difference in the magnitude of the Stroop effect when participants are sure versus unsure of the proportion of congruent trials.

It is fair to ask whether this analysis truly captures subjective awareness. Given that control is typically thought of as changes in top-down bias (e.g., Desimone & Duncan, 1995), it may be the

[2] An analysis at the level of individual trials yields the same statistical pattern of results.

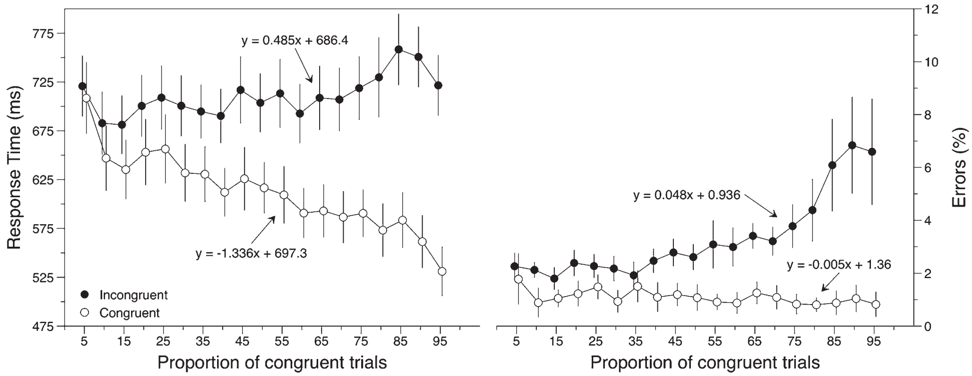

Figure 1. *Correct mean response times (left) and percentage of errors (right) in Experiment 1. Error bars represent one* SEM. *The equations indicate the best linear fit for each set of points.*

case that even if participants are unsure of the proportion, a "hunch" about this proportion may be enough to cause a shift in the bias. To assess this possibility, a regression analysis was conducted for blocks on which the participant[3] responded both incorrectly to Question 1 and sure to Question 2 (see list of questions in Method section) using proportion as a predictor of the Stroop effect in RTs and errors.[4] The 50% block was also excluded because there is no correct answer to Question 1. The data are shown in Figure 3. Restricting the analysis to this subset of the blocks means that the strategy the participant is applying (as inferred from their responses to the questions) should be the exact opposite of the strategy dictated by the proportion of congruent trials. Thus, a Stroop effect that increases as a function of an increase in the proportion of congruent trials would be very strong evidence that the congruency by proportion congruent interaction is independent of awareness of the proportion of congruent trials. Indeed, we observed this increase in RTs both with the full set of data (excluding outliers), $\beta = .481$, $t(79) = 4.87$, $p < .001$, and when the fit was restricted only to proportion values within 20% and 80%, $\beta = .481$, $t(68) = 2.49$, $p < .05$. There was no effect for errors ($p > .25$), but the slope was in the right direction. This result provides very strong evidence that the congruency by proportion congruent interaction is independent of awareness of the proportion of congruent trials.

Discussion

The findings from Experiment 1 indicate that awareness of the proportion of congruent trials had virtually no impact on the size of the Stroop effect. That is, the Proportion × Congruency interaction was statistically equivalent whether or not participants were aware of how many congruent trials there are. Given our vast proportion range, we are confident that all papers investigating this interaction have selected proportion conditions within this range. Numerically, there does appear to be a difference at the 5% and 90% conditions, but given the relatively noisy estimate of the Stroop difference at these points (comparing 8.1 to 1.9, and 8.9 to 1.1 sessions on average, see

[3] One participant is excluded from this analysis. He incorrectly answered Question 1 for most of the blocks, despite high certainty on Question 2 and accurate estimates on Question 3. Recoding his responses and including him does not affect the results.

[4] This analysis ignores the repeated measures component because each participant has data at only 4–23 blocks (mean = 11, *SD* = 7). In addition, the range of proportion values represented varies widely across participants from 15–85 (mean = 51, *SD* = 26). That said, the repeated measures analysis finds a congruency effect ($.158 \leq \beta \leq .384$) and a congruency by proportion interaction in the right direction ($-.048 \leq \beta \leq .224$), $p = .174$. The participants who fail to show an interaction in this analysis are those with the smallest range.

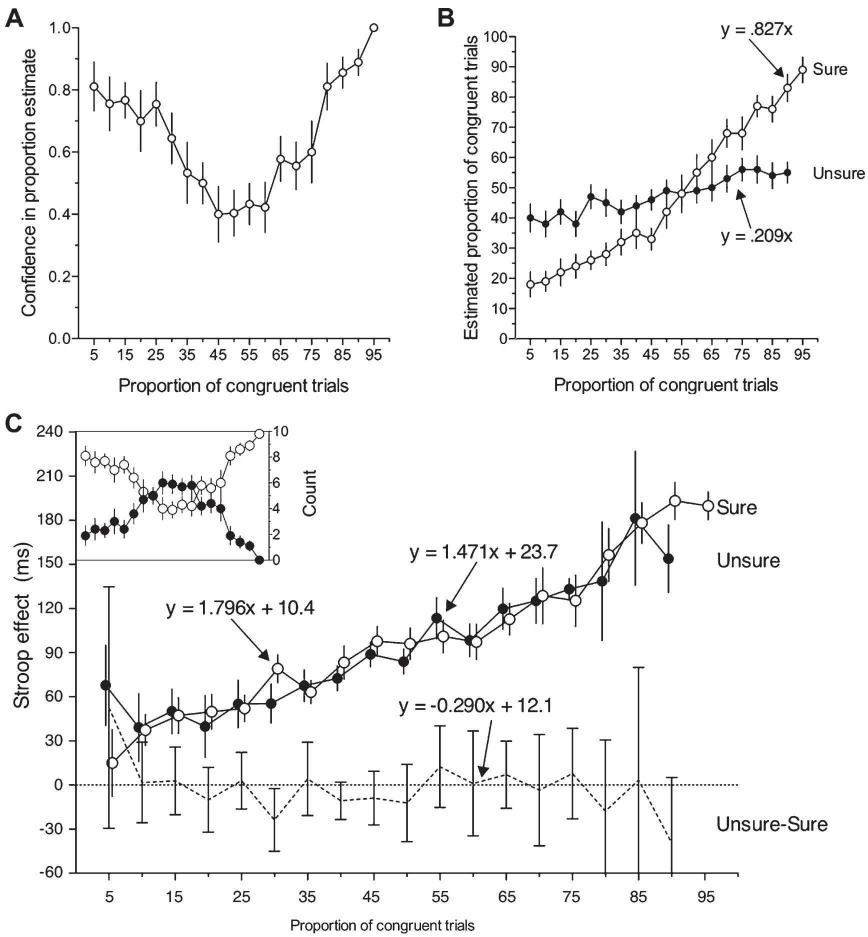

Figure 2. *A: The probability that the participant was sure of the proportion of congruent trials. B: Estimated proportion of congruent trials as a function of whether participants indicated that they were sure or unsure of the (actual) proportion of congruent trials. C: The size of the proportion by proportion congruency interaction as a function of whether participants were sure or unsure as to the proportion of congruent trials. Inset: Number of blocks going into each estimate. Error bars represent one* SEM. *Error bars with hats represent 95% confidence intervals.*

inset of Figure 2C), it is difficult to make a strong case for this. Given the absence of an effect at the more extreme proportions, we suspect that the uncorrected significant difference in the 30% block represents a Type I error.

Thus, referring to the modulation of the size of the Stroop effect by proportion congruency as a form of "strategy" on behalf of the participant seems incorrect. The term "strategic" implies the implementing a plan of action designed to achieve a particular goal. It is difficult to imagine that one could implicitly "plan" something.

One potential caveat to this study concerns the fact that asking participants to report the number of congruent trials every 100 trials is, of course, not standard practice. This may lead participants to approach the task in a different way from normal. For example, asking questions about the proportion of congruent trials may cause participants try to keep a running tally of the number of congruent trials as they perform the task (although the first author can attest to the difficulty of doing this while maintaining fast RTs). To address this concern, we ran an additional

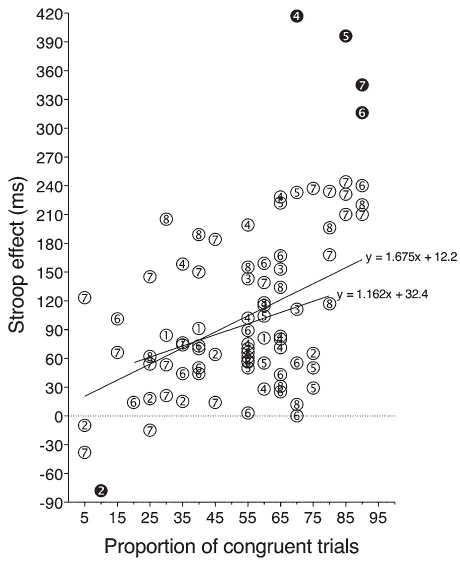

Figure 3. *The size of the Stroop effect as a function of proportion for blocks in which the participant both answered Question 1 incorrectly and were sure of this (Question 2). Circles containing the same number belong to the same participant. The five solid circles are outliers at 2.5* SDs *and were not used in the regression. Lines represent best fits at proportions from 5% to 90% and 20% to 80%.*

group of participants through a version of the experiment in which they did not receive questions.

EXPERIMENT 2

A total of 5 additional University of California, Berkeley, undergraduates (2 females) from the same pool of participants as that in Experiment 1 participated in Experiment 2. These participants performed the same task as that in Experiment 1, but were not asked the probe questions regarding their estimates of proportion congruency. All other aspects of the task remained the same. The mean correct RT data and percentage error data are presented in Figure 4.

The same repeated measures regression analysis decribed above was conducted on these data confirming the pattern of results in Figure 3. The proportion effect was significant in RTs ($-.170 \le \beta \le -.073$) and in errors ($.087 \le \beta \le .324$). The congruency effect was significant in RTs ($.317 \le \beta \le .667$) and errors ($.145 \le \beta \le .589$). And critically, the proportion by congruency interaction was significant in RTs ($.106 \le \beta \le .243$) and errors ($.121 \le \beta \le .338$).

We sought to test for differences between Experiment 1, in which participants were asked questions (Qu+), and Experiment 2, in which they were not (Qu−). Independent sample *t* tests comparing the parameter values for each factor across experiments yielded that the proportion by congruency interaction was larger in Experiment 1 than in Experiment 2, $t(12) = 2.27$, $p < .05$, in RTs (all other ps $> .25$). As is quite clear from Figure 5, both groups exhibit a strong linear relationship between the size of the Stroop effect and the proportion of congruent trials. Thus, it appears that drawing attention to the proportion of congruent trials by asking participants to

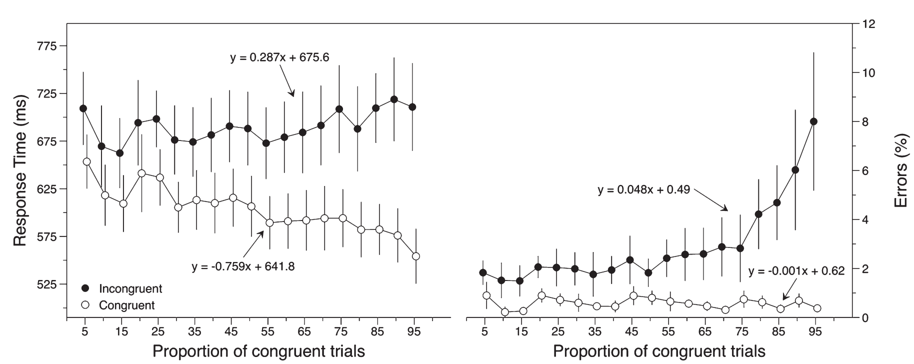

Figure 4. *Correct mean response times (left) and percentage of errors (right) for Experiment 2. Errors bars represent one* SEM. *The equations indicate the best linear fit for each set of points.*

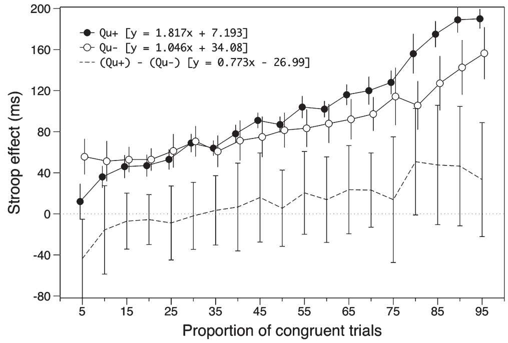

Figure 5. *The size of the proportion by proportion congruent interaction for Experiments 1 and 2. Qu+ is "with questions" (Experiment 1). Qu− is "without questions" (Experiment 2). Error bars represent one* SEM. *Error bars with hats represent the 95% confidence interval. The equations indicate the best linear fit for each set of points.*

report how many congruent trials there are (Experiment 1) affects all proportions equally.

GENERAL DISCUSSION

In this study we sought to assess the relative contribution of self-generated conscious strategies versus implicit adaptations on performance in a Stroop task. Not surprisingly, we found that when participants were encouraged to attend to the proportion of congruent trials, as they were in Experiment 1 because they were asked questions about the number of congruent trials, the size of the proportion by congruency interaction was larger than when there was no encouragement. More impressively, even though the proportion by congruency interaction was larger in Experiment 1, there was no difference in the size of this interaction as a function of whether participants were aware that there were more (or fewer) congruent trials than incongruent trials within the block. By probing the participants about the relative number of congruent trials in the blocks, we provided them with an important predictor of performance in this task. And, as is evident in Figure 2C, this predictor is used whether participants are aware of the relative proportion of congruent trials or not. As such, we can conclude that awareness of the proportion of congruent trials plays little role in the proportion congruent by congruency interaction.

Certainly, this does not mean that one is unable to apply an explicit strategy. If participants were to be informed of the composition of an upcoming block, then they might be able to implement an overt strategy to assist them in responding optimally. For example, if the participant is informed that 95% of the upcoming trials are incongruent, a participant might blur his vision so as to prevent processing of the word. Or, if 95% of the upcoming trials are congruent, he might ignore your instructions and just read the word (and get all the incongruent trials wrong). What is clear, however, is that it is not necessary to invoke this sort of strategic explanation for the standard proportion by congruency effect.

CONCLUSION

This experiment suggests that there is very little strategy that goes into the standard proportion congruent by congruency interaction. This effect is more consistent with the notion that participants are subconsciously adapting to their environment. Whether these regulatory mechanisms rely on similar neural networks is an important objective for future research. As researchers, an important question to ask ourselves is whether our study actually taps into the more deliberate form of cognitive control that relies on strategies and goal-directedness, or whether it shows how people subconsciously learn to adapt to their environment.

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