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Exploring Functions of Relational Monitoring: Relational Integration and Interference Control

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Abstract

Relational integration, the process of integrating stimuli into relations, is often thought as the primary demand of the relation-monitoring task (RMT). The current study investigated the attentional demand to inhibit irrelevant visual stimuli on relational processing in the RMT. The relevance and salience of these stimuli was manipulated while considering the complexity of relations to be integrated. 172 participants also completed Latin Square Task and Anti-saccade task as criterion individual differences in relational integration and inhibition abilities. The results revealed interference from non-target stimuli was partly accounted for by their perceptual similarity with target stimuli. The salience effect was observed but was not moderated by Anti-saccade task performance. Relational complexity was found to interact with all manipulations probing attentional function. The findings advanced our understanding of the interplay between the attentional and relational processes involved in the RMT.

Keywords: working memory, attention, inhibition, relational integration, relation-monitoring task

Introduction

Our ability to reason with novel information is inextricably linked to a dynamic working memory (WM) system responsible for maintaining and manipulating mental representations. Given the ability to well-predict fluid intelligence (Gf), WM tasks are theorised to tap processes fundamental to higher-order reasoning (Kane et al., 2007). One of these processes is *relational integration*, which captures one's ability to form new relations between representations (Oberauer et al., 2007). The relation-monitoring task (RMT) has recently been validated as a measure of relational integration and has shown an impressive ability to predict fluid intelligence (up to r = .60) (Bateman, Thompson, & Birney, 2019; Chuderski, 2014). The task involves monitoring a periodically changing 3×3 matrix of stimuli to detect rule-based matches, where rules are based on relations between a specific set of target elements (e.g., whether the 3×3 array of triplet strings contain a row or column in which the last digit of the strings are all the same, see Figure 1). The RMT has no explicit storage demand. However, while building and integrating relations is a major task demand, there is little direct evidence on how task specific features impact relational integration and inhibitory control.

Our study sought to explore the selective function of attention as outlined in Oberauer's (2009, 2021) Concentric Model of WM in relation to the RMT. We consider four factors – (a) relational complexity, (b) salience of non-target stimuli, (c) similarity of non-target stimuli, and (d) spatial distance of target stimuli.

Relational integration and the RMT

In theory, detection of a match requires participants to integrate three ending digits into relations and subsequently compare them with a generic relational rule, such as *same*, *ascending*, and *different*. Before relational integration occurs, perceptual stimuli are theorised to be represented as relational structures through *binding*. Oberauer (2009) proposes binding as the process by which the *content* of a representation is bound to a *context* in the structure, and this allows different representations to be simultaneously accessible. Binding is embedded in the attentional selection process of WM. Following Oberauer (2009), the WM system is proposed to utilise attention to efficiently select relevant information from the problem-space for goal-related processing. The selection is narrowed down across three WM components: from *activated long-term memory*, to a *direct access region* and lastly, to the *focus of attention*. Task relevant representations are activated in long-term memory (LTM) prior to entering the direct access region for further processing. The direct access region is where binding and "unbinding" processes are rapidly performed to support efficient selection for the focus of attention.

In the RMT, a match rule for the current set of trials is first activated in LTM, for instance, the concept of "sameness", which becomes the context for the current set (see Figure 1, left array). Perceptual input from ending digits also activates relevant LTM representations (e.g., the notion of numbers and their properties) for further processing. The content of each ending digit (e.g., 2, 2, 2) is then bound to its corresponding context (e.g., top, middle, bottom) and form three digit–location bindings. These bindings can then be integrated to form a new relational structure, which is subsequently selected for the focus of attention to compare

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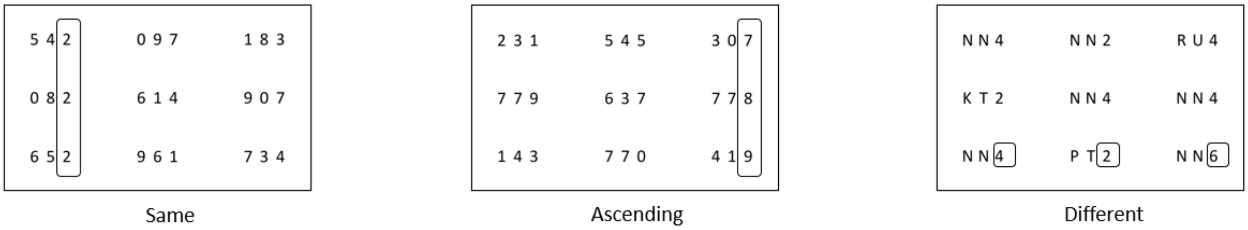


Figure 1: Example items of three match rules, as representing three complexity levels. Matches are highlighted in squares. The left, middle and right array represents an example item of each salience level (0 vs. 6 vs. 12 repeats). The replicated digit/letter was always in pairs (e.g., 77, NN). The right array is an example of non-targets being letters.

with the activated same-match rule. Unbinding occurs to dissolve the bindings so that their contents can be updated. Binding and unbinding processes ensure that the most up-to-date information is accessible to attentional selection, upon which relational processing is built.

Relational complexity of relational integration The relational integration demand of the RMT is closely related to Halford, Wilson, and Phillips' (1998) theory on relational complexity, in that the WM capacity is limited by the complexity of relations that can be instantiated. Relational complexity is determined by the number of relations that must be represented simultaneously to carry out processing. In the context of RMT, the more relational structures one needs to represent at once to detect a match, the higher relational complexity the task poses and the higher relational integration demand the task imposes. We used three match rules – *same*, *ascending* and *different* – to manipulate complexity (see Figure 1).

Following Bateman et al.'s (2019) complexity analysis, a *same* match is when three strings within a row or column end with the same digit (e.g., [2, 2, 2]). In the *same* condition, three bindings can form into a single *chunk* for the ease of processing (Halford et al., 1998). In other words, a simple *unary relation*[1] is integrated between them. Identifying a *same* match is relationally simple because a unary relation can be seen as the defining attribute of the match rule itself (e.g., in the same way red is a defining attribute of a red apple; Halford et al., 1998). An *ascending* match is when three ending digits are consecutively ascending from either left to right (within a row) or top to bottom (within a column) (e.g., [7, 8, 9]). Bindings can be chunked to facilitate the comparison of relations with the match rule. For example, in an *ascending* match [7, 8, 9], the first two bindings are chunked into [7, 8] and the second two into [8, 9]. One only needs to know both relations ([7, 8] and [8, 9]) are ascending to confirm the match. An *ascending* match therefore involves *binary relations*. However, no chunk can be formed in the *different* condition. A *different* match is when three ending digits are different from one another (e.g., [4, 2, 6]). One needs to hold each of the three bindings individually to know that 4 and 2 are different; 2 is different from 6, which is also different from 4. Hence, a *ternary relation* (e.g., three arguments [4, 2] [2, 6] [6, 4]) is required to detect a *different* match.

Salience of non-target stimuli In Oberauer's original WM theory, unbinding is critical for reducing interference from what is no-longer-relevant so that new information can be efficiently encoded for later recall. Another form of interference that has received less attention in Oberauer's WM Model may come from non-targets concurrently presented in the matrix. Non-targets are digits that constitute the broader problem space but are never part of the match (or no-match) decision, such as those in the non-ending positions (e.g., '54' in the string '542'). These digits are also activated by virtue of being a part of the problem space. They have great potential to enter WM and interfere with target selection. So far, two studies have investigated this interference effect by manipulating non-target salience (Bateman et al., 2019; Chuderski, 2014), but there is still uncertainty whether these non-targets can impair task accuracy.

Chuderski (2014) replicated one of the rule-matching digits 12 times and randomly distributed them in the array. These repeats required participants to inhibit attentional orientation to these now salient non-targets, thus adding additional inhibition demand to the task, over and above the existing relational integration demand. He did not find any main effect of interference on RMT accuracy, but this may have resulted from the use of a simple relational rule, which did not well distinguish between those who were better at inhibitory control and those who were worse.

Bateman et al. (2019) included three levels of interference, varying the number of repeats presented as pairs in non-ending positions. Similar to Chuderski's (2014) finding, no main effect of interference on RMT accuracy was observed after controlling for relational complexity. However, reanalysis of Bateman et al.'s (2019) work (Birney, in preparation) revealed that the total number of trials in each interference condition was largely unbalanced and when this was controlled for, a significant interference main effect and a significant interaction between interference and relational complexity was observed. Given these inconsistent findings outlined, further research into the non-target interference effect and the inhibition demand it poses to the RMT is warranted.

[1] Note that Bateman et al. (2019) classified the *same* condition as entailing binary relations, however we feel this was inaccurate.

Following Bateman et al.'s (2019) work, we used three interference levels – with 0, 6, and 12 repeats distributed randomly as non-target duplicates (see Figure 1). Note that repeats were always presented in pairs and would never show up alone in any non-ending position. Unlike Bateman et al. (2019), this allows for greater control over the amount of interference at each level. By having 6 repeats in the problem space, non-targets become more perceptually salient than the targets within the same string. Salient non-targets can induce additional demand to inhibit attentional orientation, on top of the relational integration demand already present in the task. However, Bateman et al. (2019) argued that when the number of repeats increases to 12, relational processing should become easier as the amount of variation between non-targets is greatly reduced in the problem space, and consequently, the high number of repeats may instead cue participants to the ending digits and benefit task performance. While Bateman et al. (2019) did not find evidence for this, we argue that this may be due to the trial generation process used.

Similarity of non-target stimuli A novel aim of our study, relative to previous work with the RMT, was to empirically validate the attentional mechanism as theorised in Oberauer's Concentric Model through manipulating non-target similarity (Oberauer, 2009). It has been well established in the visual search literature that increasing the similarity between targets and distractors can make the target search more difficult and lead to less efficient encoding of the target (Duncan & Humphreys, 1989). In the context of the RMT, the focus of attention can erroneously select one or more non-targets for relational processing (e.g., form relations between a non-target binding and a target binding). Non-targets appear perceptually relevant to the task because they share numerical features with the targets and have considerable potential to enter the direct access region, form into bindings, and compete with targets for attentional selection. One possible way to minimise non-target activation is by reducing their relevance to the task by presenting them as letters (see Figure 1, right array).

We hypothesised that changing non-targets to letters can greatly reduce the possibility of making a selection error. Not only are letters less likely to be encoded (letters barely have any relevance for the task), they also significantly reduce the absolute number of digits in the problem space, thus creating fewer selection competitions. Additionally, selection errors should be more likely to occur when attentional demand is high, such as when the relational rule is complex (e.g., detecting a *different* match).

Spatial distance of target stimuli We consider letter non-targets as having negligible effect on task accuracy and in fact, if there is anything 'interfering' about them, it should only relate to the way they are spaced out in the problem display. Note that non-targets are necessarily always presented in-between targets within a row, whereas in columns, targets always locate close to each other. In contrast to adjacent targets, forming new relations between spatially distant targets seems to be a less efficient process. Identifying row matches should be more attentionally demanding due to increased susceptibility to selection error.

Individual differences If the manipulations tap into the processes we have proposed, then individual differences in capacity to inhibit interferences should moderate the salience and similarity effects, and relational integration ability should moderate the complexity effects. We use Anti-saccade task (Friedman & Miyake, 2004) to assess inhibition ability and Latin Square Task (LST) (Hearne, Birney, Cocchi, & Mattingley, 2020) for relational integration ability.

Aims and Hypotheses

Building on Chuderski (2014) and Bateman et al.'s (2019) work, we expected a higher performance cost as complexity level increases, which should be mitigated by relational integration ability (H1). We hypothesised that the RMT accuracy would be higher when non-targets were letters compared to numbers, and this effect would be more pronounced as complexity increases (H2). To test our assumption about the selection function of attention, we expected that the lower accuracy for row matches (compared to column matches) should be more profound when non-targets were numbers compared to letters (H3). We also expected an interaction between relational complexity and match location (H4). Regarding our salience manipulation, the 6 repeats condition would interfere most with task performance, but the associated performance cost would be minimised by high inhibition ability (H5). Finally, the lower accuracy in the 6 repeats condition was hypothesised to be more pronounced as complexity increases (H6).

Method

Participants

A total of 188 undergraduate psychology students from the University of Sydney participated in the study. The study was conducted online. 16 participants were excluded for low engagement in the RMT task or a lack of either Anti-saccade or LST data. The final sample consists of 172 participants (114 females), with a mean age of 20.28 (SD = 3.33).

Materials and procedure

RMT The task presented a 3 x 3 grid of three-symbol strings, updating across trials. All of the 9 strings were ended with digits. Participants monitored whether the ending digits within a row or column conformed to a predetermined rule. They were instructed to respond by pressing the L key on keyboard as soon as they identified a match. If none of the row or column matched the rule, participants responded with the A key on that trial. Participants were informed about all possible match rules (same/ascending/different) in the instructions. For the ascending rule, they were explicitly told that the digits were on a scale from 0 to 9 and possible matches ranged from [0, 1, 2] to [7, 8, 9], where [7, 8, 9] being the last possible ascending order. Participants were given 6 practice trials for each rule with feedback. After the task officially began, a reminder of the response keys (A for no match, L for match) was always displayed at the bottom of the screen, with the current match rule at the top. The response window was 5.5 s for each trial and the interval between trials was 100 ms.

For the salience manipulation, non-target repeats would never occupy all non-ending positions within the same row or column (e.g., strings such as 770, 778, 776) because they might overly cue participants to ending digits and offset any interference effect in the 6 or 12 repeats conditions. In match trials, the repeat was one of the three ending digits involved in the match. In no-match trials, a random ending digit was chosen as the repeat.

For the similarity manipulation, the first two digits of the number triplets were consistently replaced with letters in the letter condition. Each possible digit in the non-ending positions was matched to one letter from the alphabet using a random letter generator. Letter G, H, I, O, Q and Z were excluded to avoid perceptual confusion with digit 0, 1, 2, 5 and 6. The ending digits in the letter trials were always the same as the corresponding number trials. For the complexity manipulation, interference unrelated to our research interest was controlled for.

Anti-saccade Task The Anti-saccade task is a measure of inhibition ability where suppression of an automatic attentional response is required (Friedman & Miyake, 2004). Participants were instructed to attend to the direction of an arrow and respond with the corresponding key on keyboard as accurately and quickly as possible. A cross first appeared at the centre of the screen for 1000 ms. It was then removed, and a square appeared briefly for 150 ms at either left or right side of the cross. The square was a distractor that needs to be inhibited to detect the target coming after. The target showed up in the opposite direction to the square and was masked after either 200, 500, or 1500 ms, which defined the three blocks of 25 trials that were presented in random order. Participant performance was measured as the mean accuracy across three blocks.

Latin-Square Task The Latin Square Task (LST) is a criterion measure of relational integration as it requires integrating relations between rows and columns for pattern completion (Birney, Halford, & Andrews, 2006). The task presented participants with a 4×4 matrix with shapes (circle, triangle, square and cross) in some of the cells for 5000 ms (see Figure 2). The task was to determine which shape could fill the cell with the '?' according to the rule: each shape can only occur in each row or column once. After the matrix disappeared, participants chose a response shape. They completed as many items as they could in 8 minutes. Performance was measured as the ratio of correct responses to number of items attempted.

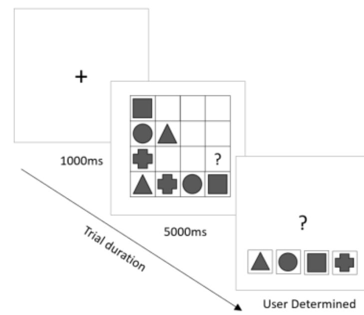
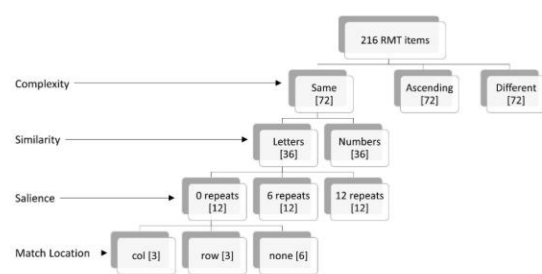


Figure 2: The Latin Square Task procedure, adapted from Hearne et al. (2020).

Design

The study adopted a (3×3×2) within-subject design. Our three manipulations, *relational complexity* (same, ascending, different), *non-target salience* (0 repeat, 6 repeats, 12 repeats) and *non-target similarity* (number, letter), and match *spatial distance* (row, column) were counter-balanced. In the RMT, all participants completed 6 blocks presented in random order: *same–number*, *same–letter*, *ascending–number*, *ascending–letter*, *different–number* and *different–letter*. Three salience levels were balanced within each block (see Figure 3). Each block had 36 trials and half of them were matches. There was only one match on each match trial which



occurred equally likely in all rows and columns.

Figure 3: The number of trials at each task level (in brackets).

Results

The probably of a correct response in the RMT task is the dependent variable (i.e., RMT accuracy). Hypotheses were tested with multi-level modelling approach and the effect of each independent variable was operationalised as contrasts. All regression analyses were conducted with R version 4.2.2 using glmer from the lme4 package. The reported regression coefficients and confidence intervals are in the odds-ratio scale. Two glmer models were run, one with LST as the moderator, and the other with the Anti-saccade scores as the moderator. The overall model R^2 was 0.133 and 0.130, respectively. These overall R^2 values indicate the effects, while statistically significant, were small. Further research into the generalisability of our results will be necessary.

Complexity

Controlling for similarity and salience, RMT accuracy was significantly lower in the *ascending* and *different* conditions on average, compared to the *same* condition (OR = 2.78, CI = [2.62, 2.95], p < .001). The performance cost associated with increased complexity was moderated by LST performance (OR = 1.13, CI = [1.07, 1.19], p < .001), such that higher LST performance was associated with a less pronounced complexity cost. The RMT accuracy was lower in the *different* compared to the *ascending* condition (OR = .66, CI = [.63, .70], p < .001). This complexity cost was also moderated by LST performance, in that it was more pronounced with lower LST performance (OR = 1.09, CI = [1.03, 1.15], p = .003).

Similarity

RMT accuracy was significantly higher when non-targets were letters compared to numbers, controlling for complexity and salience (OR = 1.15, CI = [1.09, 1.21], p < .001). The higher accuracy for letters was more pronounced in the *ascending* and *different* condition on average, compared to the *same* condition (OR = .81, CI = [.72, .91], p < .001). The higher accuracy for the letter condition was also more profound when the match rule was *different* compared to *ascending* (OR = 1.12, CI = [1.01, 1.25], p = .04).

Salience

Controlling for complexity and similarity, RMT accuracy was significantly lower in the 6 repeats conditions compared to 0 and 12 repeats on average (OR = .94, CI = [.89, .99], p = .027). The accuracy was significantly higher when there were 12 repeats compared to when repeat was absent (OR = 1.13, CI = [1.06, 1.20], p < .001). As shown in Figure 4, the salience effect appears to differ depending on the match rule, thus it was further analysed for each complexity level. When match rule was the *same*, there was a significant linear effect of salience (0 vs. 12 repeats) (OR = 1.56, CI = 1.37, 1.78], p < .001). The quadratic effect (6 vs. 0 and 12 repeats) was also significant (OR = .86, CI = [.77, .95], p = .005). Only the quadratic effect was significant when match rule was *different* (OR = .91, CI = [.84, .99], p = .022). Neither of the quadratic or linear effect was significant for the *ascending* condition. In addition, these salience effects were not moderated by Anti-saccade performance.

Spatial Distance

RMT accuracy was significantly lower when matches were in rows than in columns, controlling for complexity, similarity and salience (OR = .90, CI = [.84, .96], p = .001). The lower RMT accuracy was more pronounced when non-targets were letters compared to numbers (OR = .87, CI = [.77, .99], p = .04). The match location effect (column vs. row) appears to differ depending on complexity (see Figure 5), therefore it was further analysed for each relational rule. The RMT accuracy was significantly higher for column matches when match rule was the *same* (OR = .59, CI = [.52, .67], p < .001). When match rule was *ascending*, accuracy was significantly higher for row matches compared to column matches (OR = 1.17, CI = [1.05, 1.30], p = .003). The accuracy did not differ between column and row matches for the *different* condition.

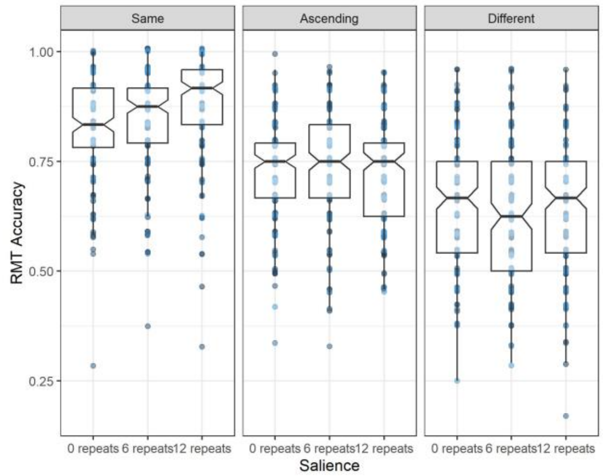


Figure 4: Violin plot of the non-target salience effect for each complexity level.

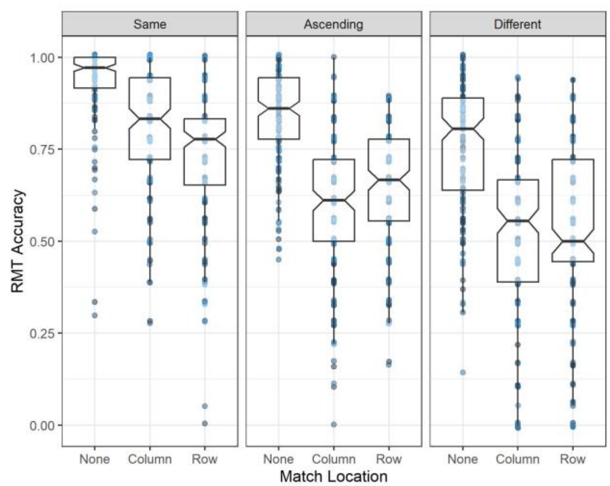


Figure 5: Violin plot of the match location effect for each complexity level.

Discussion

The RMT in theory is a processing-only WM task tapping the process of relational integration. We explored the potential interference effect from non-targets by manipulating their perceptual salience and similarity with targets. The findings importantly shed light on the attentional demand the task requires by taking relational integration function into account. Firstly, we were able to replicate previous findings on the effect of complexity by revealing a larger performance cost as complexity level increases, which was also in turn moderated by relational integration ability (measured by the LST). Secondly, we demonstrated an additional demand to resolve interference from non-target stimuli and identified potential ways to facilitate relational processing.

Consistent with our hypothesis, changing non-targets from numbers to letters facilitated RMT performance. By making non-targets appear dissimilar to targets, we were able to decrease their relevance to the task and this in theory should lower their level of activation relative to target stimuli. The benefit of using letter non-targets was also more pronounced with higher complexity level, which suggests the necessity for participants to deal with complexity while mitigating the negative influence from non-targets. To our surprise, the letter advantage was more distinct when matches were in columns compared to rows. We initially speculated a greater cost to RMT performance when identifying row matches with number non-targets in-between, as this would increase the chance of erroneously selecting non-targets for relational processing. One possible explanation is that as targets became adjacent to each other, so did non-targets and therefore the strong interfering effect from numbers may offset the benefit of having matches in columns. Overall, the results reiterate the benefit of having letters as non-targets especially when targets were spatially adjacent.

Spatial distance between target stimuli also plays a role in the process of relational integration. There was an advantage of column matches over row matches when the match rule was the *same* whereas for the *ascending* rule, identifying row matches produced better performance. This may be due to the specific features of the match rule that provided unique benefit for scanning. As forementioned, interference from non-targets may be pronounced by having adjacent targets, but the benefit associated with column matches could outweigh its downside considering the attentional demand to identify a *same* match should be relatively low. The reversed advantage for row matches may be the result of an alignment of left-to-right scanning and the sequential order of *ascending* match (Bateman et al., 2019). However, this explanation is only tentative since we did not include any measure of scanning habit. Importantly, the results by far may point to an inherent attentional process of selecting out individual targets and subsequently integrating them for relational processing across rows and columns.

Our salience manipulation also interacted with relational complexity. Although the hypothesised quadratic effect was only observed for the *different* rule, there was a clear advantage for 12 repeats when rule was the *same*. It may be the case that these salient non-targets only appeared interfering when the task was relationally complex, as it would require an increasing ability to inhibit interference. We refrained from making this speculation as none of our salience effect was significantly moderated by Anti-saccade performance. Nevertheless, we were able to demonstrate that the RMT was sensitive to both target and non-target manipulations and the resulting combined effect pertaining to attentional processing. For instance, when there were 12 repeats in the problem space, each row or column always had two repeats in two of the three strings. This would give the *same* condition an edge as these non-targets could form into a part of the match jointly with the targets (e.g., 065, 555, 555 or LN5, TT5, TT5), thus making the detection of match relatively easier compared to other match rules.

One of the limitations of current study is that we did not have a direct measure for attention to further validate our hypothesised task demand to resolve interference while integrating relations. Future research may introduce eye-tracking technology to address this issue especially when interference is manipulated. We only used one task for each of our criterion individual differences measures, which may not well capture the underlying latent variable. Although we found evidence for the moderation effect of LST performance, previous work with the LST has primarily used an untimed variant to measure the relational integration ability. In the current study, with the goal of tapping sensitivity to relational integration demands, a time-limited version described by Hearne et al (2020) was used. While this research suggests the task has construct validity, further investigations are necessary. Furthermore, the lack of criterion measure may potentially explain why we failed to find a significant moderation effect with our Anti-saccade task. A recent review paper on intelligence theories pointed out that the Anti-saccade task may be a better measure of processing speed than inhibition (Frischkorn, Wilhelm, & Oberauer, 2022), which again stresses the need to have a composite of measures to attain valid and reliable measurement. Although the current study primarily focuses on the attentional demands of the RMT, the task's theoretical link with intelligence is perhaps of particular interest to future WM and intelligence research. Bateman et al. (2019) had validated the task as a strong predictor of fluid intelligence and our continuation of their work reveals an additional attentional demand to maintain task goal. It is worth considering the task's attentional control demand as it is thought of as a contributor for the fluid intelligence and WM relationship (Shipstead, Harrison, & Engle, 2016).

In conclusion, this study provides evidence for interference coming from irrelevant non-targets in the RMT. Changing non-targets to letters significantly benefited task performance. The RMT task as a relational integration task is sensitive to the complexity of relations, the perceptual salience of non-targets and the location of the match. These results shed important light on the task's attentional aspect by highlighting the need to select targets for relational processing while resolving interference from irrelevant non-target stimuli. Future studies of the RMT are encouraged to consider relational processing in light of its attentional demands.

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