Modeling Control Strategies in the N-Back Task

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Abstract

Two studies aiming to investigate the use of cognitive control strategies in the N-Back task are presented. The first study identified a behavioral effect that seemed indicative of participants' proneness toward using high- versus low-control strategies. Two ACT-R models of N-Back implementing the two hypothesized strategies were developed. Model simulations were used to identify the proneness toward using high- versus low-control strategies by the individual participants in the second study. An independent measure of control – Stroop interference – was used to validate the predictions of the two models.

Introduction and Background

Cognitive control processes are often postulated to account for behavioral effects that cannot be explained based solely on relatively better-understood cognitive processes such as perception, language or memory. Some tasks are believed to require more cognitive control than others (Garavan, Ross, Li, & Stein, 2000). This paper aims to demonstrate that there are also differences among individuals with regard to whether or not certain cognitive control processes are employed in a particular task.

The N-Back task requires judging whether a new item is identical to the *n*th-item back in a sequentially presented list of items (McElree, 2001). For example, in the sequence < M_3 A_2 R_1 A_0 > of the 2-back task, the current item (A_0) is identical to the 2nd-item back (A_2). The task requires keeping available the most recent *n* items to be compared with the incoming item. Although at each particular step only the *n*th-item can be a target, items with indexes between 0 and *n* must be remembered because they may be targets in the following steps (Awh et al., 1996). For concision, the set of the most recent *n* items will be referred to as the *rehearsal window*.

The involvement of executive control processes in N-Back is justified by the necessity to interleave different subtasks: processing incoming information, maintaining activation of recently processed and potentially relevant information (rehearsal), and discarding recently processed but irrelevant (potentially interfering) information. Evidence that these subtasks are concurrently executed comes from fMRI studies showing activation in Broca's area (BA44) indicating articulatory rehearsal, Posterior parietal area (BA40) indicating short-term storage, and Dorso-Lateral Prefrontal Cortex (BA9/46) indicating excitatory or inhibitory modulation of activation in other areas (Cohen et al., 1997; Miller & Cohen, 2001; Owen, McMillan, Laird, & Bullmore, 2005).

One of the functions of the cognitive system is to keep active the information that is relevant to the task at hand. Usually, the most frequently and recently processed information is most likely to be relevant to the current processing (Anderson, 1989). In this case, the relevant information is kept active simply because it has residual activation from recent processing. The residual activation that an item bears for a while after its use is beneficial when the item is reused, and the probability that an item will be reused gradually decreases with time. However, in the N-Back task (as well as in other tasks of this type), the switch from relevant to irrelevant is instantaneous, instead of being gradual. When an item reaches the index *n*+1 it becomes totally irrelevant. In this case, its residual activation is not only useless but it may cause interference. An active control mechanism is needed to temporarily increase or decrease activation of a particular item depending on whether or not this item is relevant for the current state of the task.

First Study

The goal of this study was to investigate behavioral effects and individual differences in performing the N-Back task as basis for building cognitive models of this task.

Participants

Forty-one volunteers from the Carnegie Mellon University's community participated in this study (average age 26; 23 women and 18 men). They received a fixed amount of monetary compensation for their participation.

Design

This study used a within-subjects design with three conditions: 2-, 3-, and 4-back, administrated in this fixed order.

Materials

The N-Back task was administrated with the aid of dedicated software. Stimuli were capital letters appearing on the computer's screen one after another at a rate of 2.5 seconds per stimulus. Each participant received approximately 10 targets and 5 foils per condition. Reactions from participants were taken with the aid of a standard keyboard, and written feedback was presented on the screen.

Procedure

The administration of the N-Back task was based on a continuous recognition paradigm, that is, there was one stream of stimuli per condition and judgments were made after each item was presented. Based on these judgments, an item could be classified as: *target* (positive test probe) when it was identical with the *n*th-item back; *foil* or *lure* (negative test probe) when it was identical with the item presented at position *n*-1 or *n*+1 back; *distractor* (non-test probe) when it was not identical with a recently presented item. Occurrences of targets and foils in the stream of stimuli were not interleaved with one another; they were separated by a variable (random) number of distractors. Thus, the moment of occurrence for a target or a foil was unpredictable for the participants.

Participants were instructed to hit the key "M" on the keyboard when the current stimulus was identified as a target and the key "Z" when the current stimulus was identified as a foil or distractor. For the latter case, a non-reaction was also considered a valid option. Feedback was offered only for correct and erroneous reactions; feedback was not offered in case of non-reactions. A performance score increasing and decreasing in value with correct and incorrect reactions to targets, respectively, was continuously displayed on the screen.

Results

Table 1 presents the rate of correct reactions to targets and foils by condition. In general, correctness decreases with *n*; this effect is consistent across participants and in accord with previous studies (McElree, 2001).

Table 1: The rate of correct answers by condition.

	N2	N3	N4
Targets	0.72	0.55	0.46
Foils	0.84	0.57	0.59

Unexpectedly, the correlation between correctness on targets and correctness on foils was negative (r_{39}=-0.53, p=0.0004). Participants tended to score either high on targets and low on foils or vice-versa. This is an indication that some of the participants manifested what we called a "react-to-repetition" effect: they were tempted to react to a repeated item regardless whether they knew or not that it was a target or a foil. Since the number of targets was higher than the number of foils such a strategy would pay off overall. Other participants, who scored low on targets, scored high on foils because non-reaction to foils counted as correct answer. In both cases the correctness score was artificially increased.

An indication of possible use of different strategies was the so-called *serial position effect*. The serial position of an item is its distance from the last target or foil in the stream of stimuli. For example, the current target (T_0) in the following stream of targets (T) and distractors (D) <T_1,D,T_1,D,D,D,T_0,D,T_0> appears on the fourth position after the previous target (T_1), so its serial position is 4. Some participants decreased their performance with serial position (see Fig. 1), and this may be an indication of using a high-control strategy.

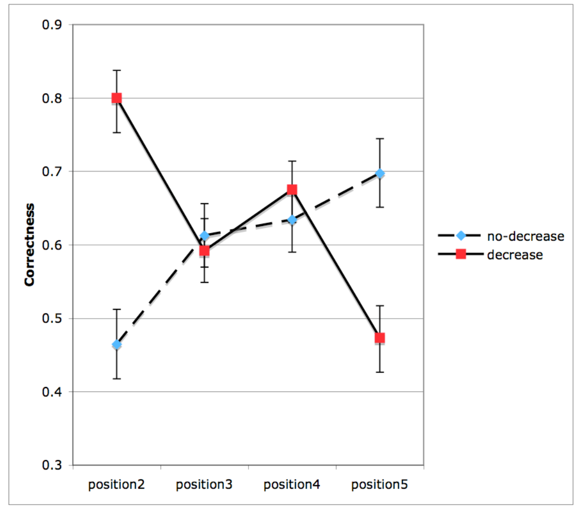

Figure 1: The serial position effect.

The two groups in figure 1 were formed by visual inspection of data of individual participants. The group showing the serial position effect ("decrease") is composed of 17 participants while the group not showing this effect ("no-decrease") contains 24 participants. The apparent increase in performance with serial position for the "no-decrease" group is most probably caused by the artificial increase in correctness due to either reaction-to-repetition or non-reaction, as described above.

Discussion

This study allowed us to gain some initial insight into how participants approached the N-Back task. The unexpected negative correlation between correctness on targets and correctness on foils made us aware of the importance of distinguishing between *judgments of familiarity* and *judgments of recency* in the N-Back task (McElree, 2001). A judgment of familiarity refers to recognizing whether or not an item has been recently presented. A judgment of recency involves deciding whether the recently presented item appeared in a particular position (e.g., *n*-back). The latter type of judgments helps in differentiating targets from foils and is more likely to require cognitive control processes (Smith & Jonides, 1999).

When participants relied solely on correct judgments of familiarity and reacted to any repetition, their correctness on targets was artificially increased (since there were more targets than foils in the stream of stimuli) at the expense of decreased correctness on foils. When a repeated item was not recognized as familiar (i.e., recently presented), a non-reaction caused low correctness on targets and artificially high correctness on foils (because non-reaction to foils counted as correct answer). These two effects combined caused the negative correlation between targets and foils. Relying solely on judgments of familiarity could be a deliberate strategy or just a consequence of failed judgments of recency.

With regard to judgments of recency, participants seemed to employ two different strategies:

- One group of participants manifested the serial position effect – decrease in performance with serial position. This effect can be explained only by assuming that participants used some sort of rehearsal and this processes was vulnerable to distraction. Participants tried to actively maintain the rehearsal window and discard past items falling outside of it. The more distractors were to be discarded from the rehearsal window (i.e., the higher the serial position), the lower the accuracy of recency judgments.
- Another group of participants does not show any behavioral trace that could indicate the use of a rehearsal process. It is unclear on what these participants base their judgments of recency. A possible explanation is the "time tag" account of Yntema and Trask (1963). They suggested that one component of the memory trace of a past event is a tag that in some way directly indicates when the event occurred.

In conclusion, this exploratory study showed us that N-Back is a task prone to strategizing. The negative correlation between correctness on targets and correctness on foils was an artifact caused by the relative frequencies of targets and foils in the stream of stimuli and the way responses were collected (non-reactions to foils counted as correct responses). The serial position effect allowed us to hypothesize that some of the participants used a high-control strategy based on rehearsal, while other participants used a low-control strategy based on time estimation.

ACT-R Models of N-Back

Based on the insight gained in the first study, two ACT-R models of N-Back were developed corresponding to the two aforementioned strategies participants were assumed to employ for making judgments of recency. A high-control model implements a rehearsal mechanism with the aid of the articulatory loop (Baddeley, 2000) and a low-control model implements the "time tag" account (Yntema & Trask, 1963). These two models differ from each other only with regard to the control strategy they implement; for the rest, they are identical in the sense that they have the same architectural parameters.

High-control Model

The main assumption of this model is that participants maintain a rehearsal window of size *n*, and actively suppress items that are dropped from this window. One way to implement a rehearsal window is by making use of the phonological loop. Phonological rehearsal is supported by our own behavioral observation (sometimes participants would vocalize aloud), reported empirical effects showing decrease in performance when phonological rehearsal is suppressed (Baddeley, 2000), and brain imaging findings showing activation of Broca's area during performance on the N-Back task (Awh et al., 1996).

The model attends to incoming stimuli and judges their familiarity, that is, compares them with past items retrieved from declarative memory. Due to ACT-R's memory decay mechanism, only a few of the most recent items can be retrieved, and the chance of an item to be retrieved increases with its recency. This is the main reason for the observed decrease in performance with *n* (see Table 1 and Figure 2).

As processing progresses through the stream of stimuli, the model develops and maintains the rehearsal window. When a new stimulus is visually perceived, it is also sub-vocalized, thus its sound is made available to the auditory module. However, the auditory module cannot attend to it immediately because it is busy with attending past and rehearsed items; it just adds it to a cue of items to be attended to later as the auditory module becomes available. In the interval between two stimuli (2.5s), the model tries to sub-vocalize the most recent *n* items. They are taken from the cue of the auditory module (the phonological store).

When the current item has been found to be a repetition of a recent one (a judgment of familiarity), it is also matched against the content of the aural buffer to allow a judgment of recency: if its content is the same as the content of the item in the aural buffer it is judged as target, otherwise it is judged as foil. A judgment of recency is as accurate as the phonological loop is.

The proper functioning of the phonological loop depends on reliably maintaining its size and content. This amounts to discarding an item from the loop whenever a new one is added and preventing discarded items from reentering the loop. Discarded items can reenter the loop via retrieval. An inhibitory control process is necessary to ensure that discarded items do not reenter the rehearsal window. A temporary storage buffer (ACT-R's imaginal buffer) holds the discarded items and spreads negative activation (i.e., suppression) to their corresponding elements in declarative memory. This way the model ensures that discarded items are not retrieved and cannot reenter the rehearsal window. However, the amount of available suppression is limited and it is evenly spread among all discarded items. Thus, the more items are to be suppressed, the less effective suppression is. This is how the model shows the serial position effect. Evidence for linear increase in activation of cortical areas involved in rehearsal with working memory load has recently been reported (Zarahn, Rakitin, Abela, Flynn, & Stern, 2005).

Low-control Model

The main assumption of this model is that participants are not rehearsing. They make judgments of recency based on learned time estimations. This assumption is inspired by the "time tag" account (Yntema & Trask, 1963) and is supported by our results from the first study showing that some participants do not manifest the serial position effect.

The low-control model makes judgments of familiarity in the same way as the high-control model. The key difference is in making judgments of recency. When an item is encoded it is attached with a time tag specifying the moment of its encoding. The temporal module of ACT-R is used for assigning time tags and making time estimations (Taatgen, Anderson, Dickison, & van Rijn, 2005). The default parameters of this module were used. When a recent item that is identical to the current item is retrieved, the model determines the time lag between the two presentations and tries to determine whether this time lag is equal to the target duration – the one needed for making correct judgments of recency. The model does not know in advance what the target duration is and has to learn it from its own experience. As a result of this learning process, any correct estimation of how long ago the *n*th-item back has been presented can serve as target duration. Thus, the model tries to retrieve the target duration and, if a correct estimation of it cannot be retrieved, the model reacts to a repeated item as it were a target. This reaction causes the system to produce feedback and the model uses this feedback to tag its recent estimation as correct or wrong. If this estimation happens to be correct it will be retrieved next time when the same time lag is found between a current item and a recent one. The more correct estimations are accumulated in memory the higher the chance that the model will make correct judgments of recency. Due to the intrinsic noise of the temporal module, time estimations are never perfect.

The essential characteristic of this process is that it does not depend on the serial position at which a target (or foil) is presented.

Models Fit

Figure 2 shows how the two models fit the data from the first study. The two models were allowed to under-fit the data, as justified by the observation that the correctness score was artificially inflated, as explained in the sections describing the first study. The N4 condition was dropped because it had a low correctness score (see Table 1) and also a very high vulnerability to be affected by the artifact described above, as shown by the highest magnitude of the negative correlation between targets and foils in this condition (r_{38}=-0.49, p=0.002).

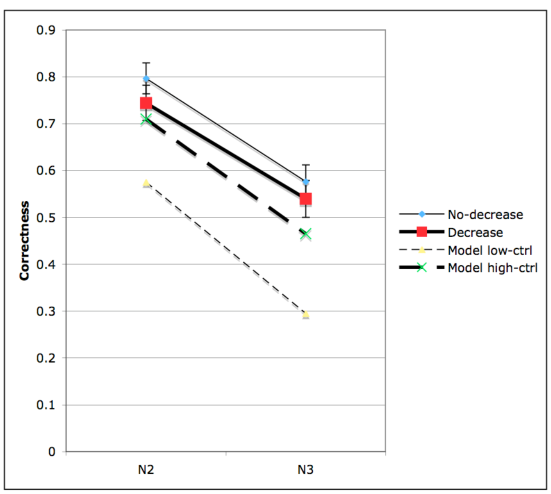

Figure 2: Data from the first study (solid lines) and model simulations (dashed lines). Thick lines indicate high control and thin lines indicate low control. Vertical bars indicate standard error of the means.

The two models show the same decrease in performance with *n* as shown in the data. The value of the retrieval threshold parameter of ACT-R was set to -0.35 (default 0.0) to fit the observed difference in the data.

The two models make qualitatively different predictions with regard to the serial position effect (Fig. 3). The high-control model predicts that maintaining a rehearsal window allows high performance at low serial positions but performance decreases at higher serial positions, as it becomes harder and harder to maintain the rehearsal window in the face of distraction.

The low-control model predicts that there is no reason for performance to vary with serial position because no rehearsal process is employed in making judgments of recency. The level of performance is given by the accuracy of time estimations, which in turn depends on the noise in the ACT-R's temporal module and the opportunities the model has to learn correct time estimations.

Second Study

This study was intended to correct the artifact found in the first study and check the hypothesis about involvement of different control strategies in N-Back. The number of foils was made equal with the number of targets and participants were asked to explicitly reject foils, that is, non-reaction to foils did not count as correct answer. These changes were expected to bring about a more valid measure of performance in the N-Back task.

It was hypothesized that participants showing the serial position effect are prone to using a high-control strategy not only in the N-Back task but also in another control-demanding task (Stroop). It was also hypothesized that manipulating the presentation rate of stimuli (inter-stimuli interval – ISI) would trigger behavioral effects that would help us distinguishing between various control strategies.

Participants

Fifty-two volunteers from the Carnegie Mellon University's community participated in this study (average age 24; 16 women and 36 men). They received a fixed amount of monetary compensation for their participation.

Design

A within-subjects design has been employed with the N-Back task and the Stroop task presented one after another in this order. Only the N2 and N3 conditions from the N-Back task were retained. The N4 condition was left out based on results of the first study showing very low performance in this condition (see Table 1). The N-Back task was administrated with two presentation rates (ISI): 2.5s and 1.5s. For this manipulation, order was counterbalanced: half of the participants received the fast ISI (1.5s) first and the other half received the slow ISI (2.5s) first. The Stroop task (MacLeod, 1991) had the three standard conditions – incongruent, congruent and neutral – randomly interleaved with one another and with an equal number of trials in each condition.

Materials

The same materials as in the first study were used for the N-Back task. Small modifications in the software were made to balance the numbers of targets and foils, collect reactions for both targets and foils, and implement the speed manipulation. A computerized version of the standard Stroop task was implemented.

Procedure

Administration of the N-Back task followed the same procedure as in the first study, except participants received additional instructions regarding how foils must be rejected. Participants were informed that a successful rejection of a foil is rewarded with one point and a correct identification of a target is rewarded with two points. Participants were not informed about the change in speed (ISI) that would occur during the experiment.

For the Stroop task participants received a short screen-based tutorial to ensure proper understanding of the task.

Results

As a result of the changes in the administration of N-Back, correctness rates were decreased overall and in particular for foils (see Table 2 and compare with Table 1), as compared with the first study.

Table 2: The rate of correct answers by condition.

	N2	N3
Targets	0.67	0.52
Foils	0.45	0.29

The correlation between correctness on targets and correctness on foils has become positive (r_{51}=0.43, p=0.001). Thus, the ability to identify targets and reject foils was better indicated by the correctness score in the second study as compared with the first study.

With regard to the serial position effect the two aforementioned models produced qualitatively different predictions (see Fig. 3). These models were used to identify each participant's proneness toward using high- vs. low-control strategies. Each participant's data were compared with the two predictions. If the data of one participant fit the prediction of the high-control model better than the prediction of the low-control model, that participant would be classified in the high-control group, and vice-versa. The root-mean-square-deviation measure was used for fitting the data of individual participants to the two model predictions. Figure 3 shows the two model predictions and the data of the two groups of participants formed based on how well individual participants fit these predictions (only serial positions 2, 3, and 4 had enough data for a reliable analysis). The high-control group was composed of 23 participants and the low-control group was composed of 29 participants. It turned out that the high-control group had also higher overall performance than the low-control group.

To verify that the two groups of participants formed based on the two different model predictions are indeed different from a cognitive control perspective, an independent measure of cognitive control was considered. Stroop interference is one of the most frequently mentioned measures of cognitive control (Miyake et al., 2000). It is computed as the difference in reaction time between incongruent and neutral trials. A one-way analysis of variance with Stroop interference as a dependent variable and the grouping variable distinguishing between high- and low-control participants as a factor was conducted and showed a significant effect in the expected direction ($F_{1,50}$=5.36, p=0.02, mean(HC)=111ms, mean(LC)=179ms). The Stroop interference manifested by high-control participants (HC) was lower in magnitude with an average of 68ms than the Stroop interference of low-control participants (LC).

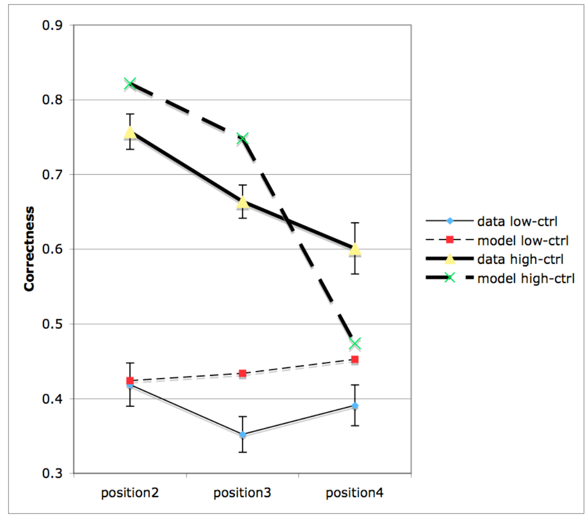

Figure 3: Model predictions (dashed lines) and their corresponding groups of participants (solid lines). Thick lines indicate high control whereas thin lines indicate low control. Vertical bars indicate standard error of the means.

It was not clear whether and to what extent performance at N-Back varied with speed. The effect of the speed change was confounded by a strong learning effect (see Table 3). Most participants who started with the fast condition (ISI=1.5s) had lower performance in this condition and most participants who started with the slow condition (ISI=2.5s) had lower performance in this condition.

Table 3: Confounding between speed and learning effects.

	Start fast	Start slow
Lower performance in the slow condition	2	16
Lower performance in the fast condition	24	9

Discussion

The interpretation that scores in the first study were biased and artificially inflated by the way the task was administrated proved correct. The changes operated to the task for the second study corrected this problem. As a consequence, the correctness score for both targets and foils now accurately indicates judgments of familiarity and recency.

Participants' proneness toward using high- versus low-control strategies was determined by the aid of the two corresponding model predictions. Participants were assigned to two different groups based on how well their behavioral data fit the simulations of the two models. Participants that were identified as prone toward using a high-control strategy showed lower Stroop interference than participants identified as being prone toward using a low-control strategy.

The speed manipulation was confounded by a strong learning effect. Both effects deserve further investigation. Arguably, speed must have a negative influence on the high-control strategy and either none or a positive influence on the low-control strategy. It would be interesting to investigate how learning relates to using these strategies and whether and when participants switch strategies.

General Discussion and Conclusion

The first study found behavioral traces (serial position effect) indicating the use of a high-control strategy in some of the participants and not in others. This effect was unequivocally interpreted as indicating the use of a rehearsal process vulnerable to distraction. Participants showing this effect were assumed to use the phonological loop to maintain active a rehearsal window of size *n* and inhibitory control to discard items falling outside of this window. Participants not showing this effect were assumed to use time estimations for their judgments of recency. Two ACT-R models were developed based on these assumptions.

Model predictions were used to categorize participants in the second study as prone to using high- or low-control strategies. High-control participants were shown to manifest lower Stroop interference than low-control participants. This result validates the assumption that the serial position effect is an indicator of using a high-control strategy. It can be argued that some of the specific modeling mechanisms used in these models are not unique. For example, a rehearsal process does not necessarily require the phonological loop (Logie, Venneri, Della Sala, Redpath, & Marshall, 2003) and rehearsal-independent judgments of recency can be implemented without assuming a time estimation mechanism (McElree, 2001). However, a distractor-suppression mechanism seems necessary to account for the serial position effect. To the best of our knowledge, no other modeling account has been proposed so far for this effect.

In conclusion, this paper argued that there are substantial individual differences with regard to whether or not certain cognitive control mechanisms are employed in particular tasks. It can be asserted that not only some tasks require more control than others but also some individuals are prone to using more control than others.

Acknowledgments

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