Motor programming disrupts verbal maintenance

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Cognitive control is a crucial aspect of our mental functioning. It constitutes the interface between thought and action by linking our perceptions, knowledge and goals to produce right behaviors (e.g., Badre, 2008). Thereby, its functioning is one of the fundamental issues for psychological researchers both in behavioral and neurophysiological approaches. Neurophysiological studies have proposed converging theories of cognitive control in relation with the architecture of the prefrontal cortex (PFC) suggesting the existence of a functional gradient along the antero-posterior axis of the PFC whereby progressively anterior subregions are associated with higher-order processing requirement (e.g., Koechlin, Ody, & Kouneiher, 2003; O'Reilly & Frank, 2006). These anterior regions organize processes in posterior regions (Koechlin, et al. 2003). They underlie the processing of information from multiple domains, such as object and spatial (Badre, 2008) and are also dedicated to domain-general monitoring of working memory (WM) (Petride, 2006). In the hierarchical cascade model of cognitive control, the 'branching control' level, located in the frontopolar cortex, is considered as the basis of all behaviors requiring simultaneous engagement in multiple tasks (Koechlin & Summerfield, 2007). This uppermost sub-division allows human to overcome the serial constraint of behavior (O'Reilly & Frank, 2006) by enabling a task to be interrupted while another is being performed. It allows switching among the more specific controlled signals at lower levels located in more posterior PFC regions. Accordingly, the posterior PFC regions are devoted to the selection of actions on the basis of content-specific conditions (Petride, 2006) and comprise additional ventro-dorsal segregations based on specialized domains (e.g., spatial vs. verbal) (e.g., Badre, 2008; Petride, 2006). This hierarchical functioning of cognitive control leads to a prediction at the behavioral

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level. If such an integrated domain-general central system exists, when two or more activities requiring cognitive control have to be performed concurrently, then they should interfere with each other whatever the level of control they involve.
At a behavioral level, these neurophysiological theories of cognitive control are highly compatible with recent domain-general accounts of WM functioning (e.g., Barrouillet, Bernardin, & Camos, 2004) suggesting that when two controlled activities have to be performed concurrently, a common general-purpose pool of resources has to be shared whatever the controlled processes and the nature of the representations they involve. This domain-general sharing has been empirically supported by studies demonstrating that several executive functions like shifting, memory retrieval, response selection, inhibition, or updating interfere with attention-demanding activities of maintenance of information in working memory (e.g., Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008). The trade-off relations between processing and storage revealed by these studies proved to occur whatever the nature of the representations involved, within the verbal and visuo-spatial domains (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos. 2007), but also for all the possible combinations of verbal and visuo-spatial activities (Vergauwe, Barrouillet, & Camos, 2010). In the same way, it has been shown that verbal memory load delays response selection concerning auditory signals (Jolicoeur & Dell'Acqua, 1998) or visual stimuli (Chen & Cowan, 2009). These trade-off relations between controlled activities pertaining to distinct domains corroborate a domain-general account of cognitive control, as suggested by the hierarchical organization of cognitive control in PFC. The fact that most of these effects are time-related lends strong support to a hierarchical model within which information is circulated through a cascade of different levels of control.

However, if the hierarchical cascade model is correct, behavioral studies can go further. Indeed, the effects of interference reported above occurred between activities necessitating the manipulation of representations in WM (e.g., locations, matrices, tones, or words) and the highest levels of control. A stronger test of the hierarchical organization of cognitive control in the PFC would be to study interference from the lowest levels of this hierarchy by demonstrating that even processes involved in controlling motor responses can interfere with WM functioning in the same extent as other attention demanding processes. For example, it is known that the reaction time (RT) to release a key for moving arm to grasp an object 30 cm away is longer (about 34 ms) than the RT to simply release the same key (Henry & Rogers, 1960). This increase in RT is thought to reflect a centrally regulated motor preparation that predates the physical movement (Jennings & van der Molen, 2005). Accordingly, brain-imaging studies have shown that the preparation of voluntary movement activated preferentially posterior regions of PFC (e.g., premotor cortex) (D'Esposito, Ballard, Zarahn, & Aguirre, 2000) and that motor complexity co-varies with the pattern of brain activation (Picard & Strick, 1996). While constituting the lower-most sub-part of the cognitive control hierarchy (D'Esposito, et al., 2000), the more a motor response is complex, the more it implies a substantial central demand (Picard & Strick, 1996). As a consequence, in the same way as concurrent task switching, response selections, and memory retrievals disrupt maintenance in WM by occupying a central bottleneck and impeding refreshing activities, programming a complex motor response such as moving the arm to reach a target should have a detrimental effect on WM.

The present study was inspired by a previous experiment showing that increasing the difficulty of response selections in a spatial task has a detrimental effect on concurrent verbal maintenance (Barrouillet et al. 2007). In a computer-paced complex span task paradigm, participants had to judge the location (either up or down) of squares appearing successively on screen while they maintained letters for further recall. The demand of these response selections was varied by manipulating the feasible discrimination of the two possible locations that were either close or distant. As expected, the *close* condition that involved the more demanding response selections disrupted concurrent maintenance and resulted in lower recall performance than the *distant* condition. The present study included a third condition named *motion* that involved the same demand of response selection as the *distant* condition, but a higher demand of motor programming: instead of keeping their fingers on the response keys as in the close and the distant conditions, participants kept their hands on table, far from the keyboard, and had to move them to press the keys. This more demanding motor programming was assumed to require cognitive control (Jennings & van der Molen, 2005).

The hierarchical structure of nested levels in the PFC (Koechlin & Summerfield, 2007) and the serial constraints (O'Reilly & Frank, 2006) of the cascade model aforementioned make that only one activity can be under cognitive control at a time. Hence, increasing the cognitive control of responses by rendering more demanding either their selection or their motor programming should have the same disruptive effect on concurrent demanding activities such as maintaining verbal information in WM. Thus both the *motion* and the *close* conditions of the location task should result in poorer recall of the letters than the distant condition. Moreover, this effect should be commensurate with the extra-time of control resulting from either the more difficult response selection induced by the *close* condition or the more demanding motor programming requested by the *motion* condition; a control experiment was conducted to assess the specific additional demand of cognitive control imposed by the more demanding motor programming in this last condition.

Method

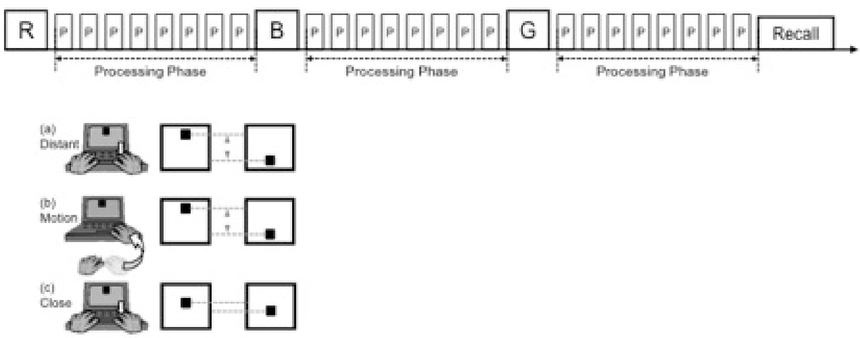
Participants

Twenty-seven participants (mean age = 19.4 years) for the main experiment and 14 additional participants (mean age = 19.8 years) for the control experiment received a partial course credit for participating.

Material and Procedure

For the main experiment, participants were presented with series of 3 to 8 to-be-remembered consonants. Each consonant was followed by 8 successive black squares (18-mm sides subtending 2 degrees in visual angle) centered randomly on one of two possible locations either in the upper or the lower part of the screen with the same frequency. In the *distant* and *motion* conditions, the two locations were 68 mm apart (6.5 degrees in visual angle), while in the *close* condition, the distance was reduced to 5 mm (0.5 degrees). Participants judged the location of the squares and gave their responses by pressing keys according to two modalities. In the *distant* and *close* conditions, participants were asked to press one of two keyboard keys on which they kept their index fingers during all the session, with the right and left keys for the lower and the upper responses respectively. In the *motion* condition, they had to move their index fingers from a given starting point on the table (18 cm away from the keyboard) to any key in a 9-key space (3 lines of 3 keys) in the left or right side of the keyboard for the lower and the upper locations respectively (Figure 1). For each series length, 2 series of consonants were associated with each of the three conditions. Irrespective of the condition, each series began by a ready signal centered on screen for 750 ms, followed after a 500 ms delay by the first letter presented for 1500 ms. After a post-letter delay of 500 ms, each of the 8 squares appeared for 667 ms and was followed by a 333 ms delay. The following consonant appeared for 1500 ms and so on. The interletter intervals were thus constant (i.e., T = 8500 ms). The 36 series were randomly presented, participants being informed about the length, the level of feasible discrimination and the motor response mode before each series (e.g., "7 letters / distant stimuli / move"). They had to read aloud each letter and to judge the location of each square as fast as possible without sacrificing accuracy. When the word "Recall" appeared, they had to write down the remembered letters in correct order. A training phase familiarized participants with the location judgment task (48 stimuli in each condition) and then with the WM task with one series in each condition. Memory performance was computed as the percentage of letters correctly recalled in correct position (Barrouillet et al. 2007). Accuracy and response times in the location judgment task were recorded. The extra-time needed for programming the motor response in the *motion* condition was evaluated in a control experiment in which participants had to judge the location of 120 squares in each of a *distant-control* and a *motion-control* conditions at the same pace as in the experiment, but without letters. In the *distant-control* condition, participants had to keep their index fingers pressing two keys of a button-box and to simply release either the left or the right key when a square appeared in the lower or the upper location respectively. In the *motion-control* condition, the button-box was located 18 cm away from the keyboard. Participants had to release the left or the right key and press any key of the corresponding space in the keyboard to give their response. The difference in mean RTs to release the button-box keys between the *distant-control* and the *motion-control* conditions was assumed to reflect the extra time needed for motor programming in the latter condition.

Fig. 1 - The upper panel illustrates the computer-paced working memory span task with a series of 3 to-be-maintained letters, each letter being followed by a processing phase of fixed duration in which 8 processing items (i.e., P) have to be processed. The response modes and the physical characteristics of the to-be-processed items are depicting for the three conditions. (a) Distant condition: participants had to stay their fingers on keyboard and squares locations were 68 mm apart, (b) Motion condition: participant had to move their hand from table to keyboard and squares locations were 68 mm apart, (c) Close condition: participants had to stay their fingers on keyboard and squares locations were 5 mm apart



Results

All participants, except one who was excluded from the analyses, reached over 70 % of correct responses in all conditions of the location judgment task. Accuracy was slightly better in the *distant* (96 %) than in the *motion* condition (92 %), the *close* condition eliciting the lowest accuracy (83 %). An ANOVA with the three conditions as within-subject factor was conducted on the percentage of letters recalled in correct order. In line with our predictions, the demand of the concurrent processing affected memory performance with 80%, 76% and 73% of letters recalled in correct position for the *distant*, *motion* and *close* conditions respectively, $F(2, 50) = 9.34$, $p < .001$, $h_p^2 = .27$. Planned comparisons revealed that recall performance was lower in the *close* than in the *distant* condition, $F(1, 25) = 15.76$, $p < .001$, $h_p^2 = .38$. Most importantly, the comparison between the *distant* and the *motion* condition revealed that motor programming had a detrimental effect on concurrent memory performance, $F(1, 25) = 6.18$, $p < .05$, $h_p^2 = .20$.

Temporal analyses were conducted to relate the effects observed in recall performance to the extra-times of cognitive control induced by the *close* and *motion* conditions compared to the *distant* condition. The mean response times in the *distant* and *close* conditions were of 346 ms and 415 ms respectively, revealing an extra-time of 69 ms required by the more demanding response selection in the latter condition. Concerning the control demand of motor programming in the *motion* condition, the control experiment revealed a difference of 51 ms in reaction times between the *distant-control* and the *motion-control* conditions. It can be observed that the decreases in recall performance caused by the *close* and *motion* conditions (7% and 4% respectively) were commensurate with the additional 69 ms and 51 ms resulting from the more demanding response selection and motor programming they respectively induced. Hence, whatever the nature of additional control required by the processing task, a trade-off function related the time during which the processing task imposed a control demand to the amount of information that can be concurrently maintained.

Discussion

With respect to the primary purpose of this study, the results are straightforward. Maintenance of letters was affected both by response selection and, more interestingly, by motor programming. To our knowledge, interference between a motor activity and verbal memory had never been reported. While the cascade model of cognitive control has essentially been corroborated by neurophysiological data such as the antero-posterior gradient of activation in the PFC, the present findings provide behavioral evidence for the hierarchical organization of nested levels of cognitive control. Though these facts are in line with the theories of WM proposing that a common pool of domain-general resources has to be shared between controlled activities (e.g., Barrouillet, et al. 2004; Barrouillet, et al. 2007), they are less compatible with Baddeley's multi-component model of WM (Baddeley & Hitch, 1974) which is very popular in neurosciences. In WM studies, trade-off relationships had already been observed between motor preparation and memory for spatial information (Smyth et al., 1999). This effect occurs when arm movements are active, but disappears when they are passive (Quinn, 1994). Authors favoring domain-specific constraints within the multi-component view of WM explained these results by arguing that passive movements do not require the manipulation of visuo-spatial information associated with motor programming (Logie, 1995). The present results rather suggest that passive movement do not disrupt memory for visuo-spatial information because they do not involve cognitive control which is in turn available for concurrent maintenance. This latter explanation is indeed supported by previous findings demonstrating that no measurable impact on concurrent maintenance is observed when the processing task (i.e., a simple reaction task) does not sufficiently solicit cognitive control (Barrouillet et al., 2007).

Moreover, the temporal analyses of the present data provided empirical support to a recent aspect of the hierarchical cascade model of the PFC (Koechlin & Summerfield 2007) according to which the 'branching control' level is crucial to overcome the serial constraint by enabling a task to be interrupted while another is being performed. This latter proposition echoes the core assumption of the Time-Based Resource-Sharing (TBRS) model of WM (Barrouillet et al., 2004; Barrouillet et al., 2007), by which a central bottleneck allows only one process to take place at a time and leads to a time-based sharing of central resources in WM. Within this background, the time during which an activity captures attention is of particular importance because it determines the time during which other activities can not take place. Given that maintenance of information in WM is achieved through controlled attention by a central mechanism based on refreshing of memory traces (Chen & Cowan, 2009), this conception leads to predict a direct and monotone function between the time during which the processing activity requires cognitive control and the memory performance, whatever the nature of this processing activity. Accordingly, the effects on verbal recall performance of both response selection and motor response programming were proportionate with their duration. Because central processes are sequentially constrained, any attention demanding activity, as low as it may be in the cognitive control cascade, delays the refreshing of memory traces and hence disrupts maintenance.

A great amount of psychological researches on cognitive control focused almost exclusively on high level and complex cognitive activities and neglected that stage that is nonetheless crucial to produce overt behavior, i.e., the motor preparation. Though being already proposed by neurophysiological theories, the close interdependence between cognition and action was here supported by behavioral evidences.

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Resumo

A organização funcional do córtex pré-frontal (PFC) das regiões anterior para a posterior, reflecte a hierarquia do controle cognitivo tal como as sub-regiões anteriores se associam progressivamente em rede de controle de ordem superior. Este estudo pretende trazer prova comportamental para duas previsões acerca do modelo de cascata. Em primeiro lugar, mesmo as áreas mais baixas da hierarquia de controle cognitivo, i.e., a programação motora, devem interferir com processos superiormente controlados tais como a preservação de informação na memória de trabalho. Em segundo lugar, este efeito disruptivo deverá ser proporcional ao tempo durante o qual o controle é necessário. Numa tarefa desenhada com o auxílio de computador, aos indivíduos, adultos, era pedido que retivessem informação escrita (letras) ao mesmo tempo que realizavam uma segunda tarefa. As exigências desta segunda tarefa definiam-se ou na fase de selecção ou na fase de programação motora para a preparação da resposta. Os resultados mostram que a manipulação, tanto numa fase como na outra, provocam efeitos negativos na memória verbal e que esse efeito é proporcional ao tempo extra durante o qual se processa o controle cognitivo quer para a selecção da resposta quer para a programação motora necessária à situação.

PALAVRAS-CHAVE: Controlo cognitivo, Programação Motora, Memória de trabalho, Interferência geral

Abstract

The functional organization of the PFC from anterior to posterior regions reflects a hierarchy of cognitive control whereby progressively anterior sub-regions are associated with higher-order control. The present study aimed at providing behavioral evidence for two predictions issuing from this cascade model. First, even the lower-most sub-part of the cognitive control hierarchy, i.e. motor programming, should interfere with higher controlled processes such as maintenance in working memory. Second, this effect should be commensurate with the time during which control is required. In a computer-paced complex span task, adults had to maintain letters while they performed a secondary task. The demand imposed by this task was manipulated either at the selection or at the motor pace programming stage of response preparation. Results revealed that both manipulations have a disruptive effect on verbal memory, and that this effect is commensurate with the extra-time during which response selection and motor programming require cognitive control.

KEY-WORDS: Cognitive control, Motor programming, Working memory, Domain-general interference