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Planning ahead through space and time: from neuropsychology to motor control

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Abstract

The executive functions have been studied separately in the fields of neuropsychology and of motor control. However, it is not clear whether across fields one is referring to similar cognitive functions. In the present study, we compared the performance scores obtained in a motor spatial-tapping task with those scores obtained in a battery of three neuropsychological tasks which assess respectively the executive functions of updating (N-back task), inhibiting (Go-noGo task) and switching (Letter-number task). Multiple regression analyses revealed significant and specific effects between the motor task and the classical neuropsychological tasks: the timing error measured at slow tempi in the tapping task predicted the scores observed in the updating task only; the spatial error at faster tempi predicted the scores obtained in the switching task only; the contact times at intermediate tempi predicted the scores obtained in the inhibiting task only. Hence, we introduce this easy-to-use non-verbal task as a novel paradigm to assess executive functioning.

Keywords: planning; executive functions; motor control; neuropsychology; regression; space; time.

Introduction

Neuropsychological approach of Planning

Research on the executive functions has historical roots in the study of patients with frontal lobe damage. These patients were the first to demonstrate disruptions to control and organize daily activities independent of any language or memory disorders (Damasio, 1994; Harlow, 1868). The so-called 'frontal' or 'executive' tasks were specifically developed to assess how the main functional deficit encountered by frontal patients, i.e. the planning of daily activities, was affected following brain injury. For example, the Tower of London (Shallice, 1982), a task inspired by a logical reasoning game (the Tower of Hanoi) was proposed to evaluate the ability to inhibit a routine schema – that consisted in producing each move in an isolated and impulsive fashion in response to the true visual configuration of the Tower – in order to define and adopt a cognitive plan to achieve the puzzle in fewer moves (see the model of SAS/GOC, Shallice, 1988). The Wisconsin Card Sorting Test (WCST, Grant & Berg, 1948), on the other hand, was proposed to target individuals' inability to switch efficiently from an ongoing plan to a novel one. In this task, perseverating errors were measured and used as indicators of cognitive flexibility (Milner, 1963). Finally, working memory tasks, e.g., the n-back task, were developed to target a person's ability to maintain a cognitive plan active and to update between relevant parts of the plan in function of a given situation. Hence, the executive functions are here directly related to the abilities to inhibit a routine schema in order to adopt and adapt a novel more cognitive plan, to maintain and update parts of a given plan across time and/or to switch flexibly from one plan to another. In the last decade, these cognitive abilities have been referred to in the literature as the inhibiting, the updating, and the switching executive functions (Miyake & Friedman, 2012; Miyake et al., 2000) and it is common today to use a multiple-test battery to assess the well functioning of the executive functions related to planning abilities.

However, it is the case that the neuropsychological tasks that are classically used to assess the executive functions suffer from a number of validity problems that limits severely the possibility to compare the functions between them. Indeed, the tasks are known to have impurity issues because of the presence of non-executive demands specifically related to the various contents that are used in the tasks (e.g., language, limb displacements, object identification, etc., Burgess, 1997; Phillips, 1997). Second, they present a lack of test-retest reliability, i.e. people can adopt different executive strategies to perform the same task across sessions (Rabbitt, 1997). For example, although the WCST has been designed to reveal a lack of cognitive flexibility, subjects may perform the task by inhibiting certain responses that are no longer appropriate (Miyake et al., 2000). Thus, scores in different sessions may reflect different cognitive strategies, with participants who are sometimes switching between rules and at other times using inhibition to solve the task. The difficulty to characterize the possible relationships between the executive functions is in itself a motivator to consider today a different approach to the evaluation of executive functioning.

Planning in the Motor Control domain

A major interest in the field of motor control is to understand how actions are coordinated to enable the execution of complex sequential motor activities, e.g. playing a musical instrument or dancing in rhythm. This question has been particularly studied in the context of sensorimotor synchronization (for a review on SMS, see Repp, 2005). Even if synchronized behaviors require motor coordination both through space and time, research has focused historically on the timing aspects of motor planning and experimental findings have led to the acceptance today of the existence of two distinct timing modes related to the control and execution of rhythmical action sequences (Robertson et al., 1999; Zelaznik, Spencer, & Ivry, 2002). The event-based timing mode is primarily involved in tasks that have a clear temporal goal, e.g. trying to keep the beat of a metronome, and is assumed to require an explicit internal representation or memory of the referential temporal interval to produce (Wing & Kristofferson, 1973). By contrast, emergent timing is assumed to arise implicitly, i.e. from the extraction of temporal regularities emerging naturally from the dynamics of movement control when actions are repeated in smooth oscillatory cycles (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Turvey, 1977). For example I can infer that "I will be late given the speed of my successive footsteps". While finger tapping is the prevailing paradigm to reveal event-based timing, circle drawing has been proposed as the exemplar task to reveal emergent timing (Zelaznik et al., 2002). In terms of statistics, negative lag-1 autocorrelation values are typically observed in finger-tapping tasks suggesting that motor responses are controlled through an internal timekeeper (Vorberg & Wing, 1996; Wing & Kristofferson, 1973). In contrast, positive or near-to-zero AC-1 values are classically reported in circle drawing tasks suggesting that other mechanisms of control enter into play and enable the implicit emergence of a certain sense of rhythmicity (Lemoine & Delignières, 2009; Torre & Delignières, 2008; Zelaznik et al., 2002). Anchoring has been described as a possible mechanism that could explain how timing emerges when movements are continuous rather than discrete. This phenomenon, commonly observed in cyclical movements, consists in a local reduction in spatial and/or temporal errors at a specific location along the trajectory path and is often observed around reversal points, i.e. at points of transition between flexion/extension movements (Beek, Turvey, & Schmidt, 1992; Roerdink, Ophoff, Peper, & Beek, 2008). This specific point of transition could be used as a referential to infer timing regularities in the case of continuous movements (Repp & Steinman, 2010).

In a recent study (Dione & Delevoye-Turrell, unpublished) the use of a unique task designed as a hybrid of finger tapping and circle drawing was suggested to reveal, assess and compare the two modes of timing between them. In this 'spatial-tapping' task, a picture composed of six discrete visual targets (disposed around a virtual circle) was displayed on a tactile screen. Participants were asked to produce discrete taps on each target, one after the other and to follow the circular trajectory with the arm at the regular pace of a metronome (from 1100 to 300 ms of inter-tone intervals, ITI). The motor actions were assumed to be discrete at slower tempi with the need of cognitive control to maintain long timing intervals through timekeeping at slow tempi; motor actions were proposed to be continuous at faster tempi through the capacity to anticipate only the point of transition between flexion/extension movements when the tempi were too fast. Autocorrelation values were measured up to ten lags to reveal event-based timing at slow tempi (negative AC-1) and emergent timing at faster tempi (positive AC-6). Furthermore, a detailed spatial analysis was conducted on the spatial endpoint distributions to assess whether the cognitive strategy was turned towards the need to anticipate the point of transition between flexion and extension movement at faster tempi. Spatial ellipses were first measured for each target. The mean area and the angular orientation of each ellipse were then computed. An orientation error was finally calculated as the angular difference between the orientation of the ellipse and the tangent to the circle measured at each target. Performance results revealed first that both the timing (% of IRI_{error}) and the spatial accuracy (mean spatial area) were perfectly maintained at slowest tempi (from 1100 to 900 ms). A first small but significant decrease in the performance arose at 800 ms and was maintained until 600 ms. For tempi that were faster than 500 ms the performance was the worst with rather large spatial and timing errors. As predicted for the timing strategies, significant negative autocorrelation values emerged at lag-1 at slow tempi only (from 1100 to 700 ms) and significant positive AC emerged at lag-6 at faster tempi only (from 500 to 300 ms). In order to assess whether the actions were controlled or not through an internal timekeeper (event-based timing), the motor delays were measured for each tempo and both lags according to the W-K model. Results revealed that the motor delays increased in function of tempi at lag-1 only, suggesting that the timing was event-based at slow tempi only in this spatial-tapping task and that other mechanisms entered into play to explain the correlation factors observed at lag-6. Finally, the spatial analysis confirmed that the endpoint distributions were more oriented in relation to the tangent to the circle at faster tempi, with the emergence of an anchor point at the point of maximal extension in the fastest tempi only.

Overall, these results suggested that in the spatial-tapping task, the timing mode was changed from event-based timing at slow tempi towards emergent timing at faster tempi. Consequently, it is possible to presume that in this motor task the cognitive demands depended on different behavioral strategies in function of the cognitive needs to actively maintain a referential timing interval in working memory (from 1100 to 900 ms), and to anticipate the spatial point of transition between the two movements of flexion vs. extension involved in the sequence (from 500 to 300 ms). An intermediate phase was here observed for those tempi between 800 to 600 ms in which the performance was decreased in space and time but in which at the same time the event-based timing strategy was efficiently maintained for 2/3 of the trials. It is thus possible that in this phase motor inhibition was used in order to avoid a too fast transition from discrete to continuous movement by making an effort to maintain attention on each discrete action in spite of the increase in temporal pressure.

From neuropsychology to motor control

In the present study, we suggest that the spatial-tapping task, a task in which several motor actions need to be planned and executed both in space and time could be an interesting method to assess the so-called executive functions. Indeed, the spatial-tapping task requires: (1) working-memory at slow tempi in order to produce discrete tapping actions in reference to memorized timing intervals, (2) the active reduction of a switching cost related to the motor switching between the two biomechanically distinct movements of flexion and extension that compose the movement sequence with the idea that bad switching will lead to poor spatial control of movement trajectory, (3) and finally inhibition of a too fast transition from discrete to continuous actions at intermediate tempi, with finger contact times that are too short to maintain high timing levels of performance.

In order to test this hypothesis performance scores were measured both in a spatial-tapping task and in a battery of neuropsychological tests assessing the three main executive functions. Multiple regression analyses were then computed to explore and reveal specific relationships between the functions.

Methods

Participants

Twenty-six right-handed students between 18 to 21 years of age and recruited from the University of Lille3 participated voluntarily in the study. All participants received an information letter and provided written informed consent. All participants performed the task with their right hand and reported having normal or corrected-to-normal vision. The protocol received approval of the ethics committee in human sciences of the University of Lille3.

The spatial-tapping task

Material & Stimuli. A picture composed of 6 black targets was displayed on a touch screen Elo Touch 19'' 1915L. The targets (10 mm of diameter, distanced of 100 mm) were placed around a virtual circle of 100 mm of radius. The participants were invited to stand in front of the screen that was placed upon a table and titled at 90 degrees of angle.

Procedure. The subjects' task was to touch each visual target one after the other, starting from the bottom right target, and moving counter-clockwise using the right index finger (fist closed). Participants were instructed to synchronize each pointing action to a series of regular auditory tones (beep duration = 100 ms) that was played through classic computer speakers. Participants were encouraged to maintain their left arm relaxed along the body side. They were clearly instructed of the goal of the task that was to be at best synchronized with the metronome. Each subject performed a total of ten trials. The initial tempo was an inter-tone interval (ITI) of 1200 ms. The temporal interval was increased by 100 ms between each trial with the fastest one being at an ITI of 300 ms. Participants were required to produce sixty taps for each trial. The total duration of the session was 10 minutes, approximately.

Performance measures.
Timing performance. Inter-response intervals (IRIs) were measured as the time interval between the start of two successive taps. Long intervals (> 2*ITI) were omitted from all calculations. The IRI_{error} was then computed as the percentage of absolute difference between each IRI and the reference ITI of a given trial. This measure served as an indicator of the magnitude of the timing error.

Spatial performance. The endpoint distributions of the pointing actions were plotted in function of each visual target position. All taps were used (ten data points per ellipse). Through vector calculations, spatial ellipses were then calculated. The mean area of the spatial ellipses was finally measured in mm^2 as an indicator of the magnitude of the spatial error (SE).

Motor Fluency. The Contact time (CT) was defined as the time of finger contact with the touch screen. This measure (in ms) was used to assess the level of control of the motor response output, with shorter CTs being related to a more fluent gesture.

Planning indicators.
Event-based vs. emergent timing. After having suppressed the first six IRIs of each trial, autocorrelation (AC) values were calculated at lag-1 and lag-6 (for details, see Vorberg & Wing, 1996). These measures served as an indicator of the timing mode that was used to guide the pointing actions with event-based timing being revealed through negative AC-1 values, and emergent timing through positive AC-6 values.

Statistical Analyses. Performance measures and planning indicators were first calculated for individual trials and then averaged across participants. Second, analyses of variances (ANOVA) were conducted with ITI as a repeated measure on measures and indicators. Fisher LSD post hoc tests were used when required and the alpha level was set to 0.05. The performance measures were then averaged within three phases for each subject according to the moment of change in planning strategy: slow or updating phase, intermediate or inhibiting phase, fast or switching phase.

Neuropsychological tasks

Material & Stimuli. The tasks were all selected from a French version of the TAP computerized battery of tests (Zimmermann & Fimm, 1994). Participants were seated in front of the computer. The experimenter provided instructions orally. The same instructions were then displayed on the screen. A familiarization trial was performed before each task. One or two response keys were used, in function of task requirements. When only one response key was presented, subjects were asked to respond with their right hand only. When two response keys were required, participants were asked to respond with their right hand on the right key, and their left hand on the left key. For each task, participants were asked to respond as rapidly as possible while maintaining a low error-rate.

Tasks procedures.

Updating & N-back task. A series of one-digit numbers were presented one after the other, in the centre of the screen (100 items that 15 target items). The subjects' task was to press the response key as fast as possible when the item on the screen was the same as the item presented two times before. Subjects were scored according to the median of their reaction times (RT).

Inhibiting & Go-noGo task. A straight or a diagonal cross ('+' or 'x') appeared briefly in the centre of the screen, for a total sequence length of 40 items. The participant's task was to press a response key as fast as possible for the diagonal cross ('x') only. The target item was present 50% of the time. Participants were scored according to the number of false responses.

Switching & The Letter-number task. A letter and a number were simultaneously presented on the computer screen, for a total sequence of 100 items. Two control conditions and one alternation condition were performed. Two response-keys were used. In the first control or *pure block* condition, the participants' task was to press the response key that was in the same hemi-field than the letter (for example, if the letter was presented on the left side of the screen, subjects had to press the left response key). In the second control condition, participants had to press the response key that was in the same hemi-field than the number. In the *alternation* condition, the participants were instructed to alternate a response to a letter, and a response to a number, from trial-to-trial, by pressing the response key that was located in the corresponding hemi-field. Participants were scored according to a *switching cost* that was measured as the difference in reaction time between the pure blocks (that were pooled together) and the alternation condition.

Statistical Analyses. Performance scores were calculated for each individual in each task and then averaged across participants. Descriptive results (mean, standard, deviation, min & max values) were then computed. $\chi2$ tests were then performed to ensure that performance scores were normally distributed across tasks.

Multiple regression analyses: ST vs. classical tasks

Standard multiple regression analyses were conducted to evaluate how well each performance scores (IRI_{error}, CTs, area) obtained in each phase of the spatial-tapping task (regressors) could predict the scores obtained in each of the neuropsychological tasks (dependent variables). The alpha value was set at 0.05. Following our hypotheses, (1) the timing accuracy in the slow phase of the spatial-tapping task (IRIerror) should require WM abilities (n-back task); (2) control of the motor response (CTs) as required in the intermediate phase of the spatial-tapping task should be an indicator of inhibition abilities (go-no-go); (3) decrease in the spatial error in the faster phase of the spatial-tapping task (area) should be an indicator of the switching abilities (letter-number task).

Results

The Spatial Tapping task

Performance results.

Timing performances. Results revealed that all participants closely followed the tempo even at fast tempi, with a maximum mean error of 8% across the ITI spectrum. As an example, the greatest errors were observed in the fastest tempo of ITI=300 ms, with IRIs contained between 276 and 324 ms. ANOVA on the IRI_{error} revealed nevertheless that the timing errors were significantly different in function of ITI ($F(9;225) = 7.685$; $p < 0.001$). Post hoc tests revealed that timing errors were larger at faster tempi, i.e. for ITI=400 to 300 ms (Mean = 7.6%; SD = 2.8%) and these values were significantly different from that measured at slower tempi (Mean = 5.9%; SD = 1.7%).

Spatial performance. ANOVA conducted on the spatial area revealed an increase in the spatial errors at faster tempi ($F(9; 225) = 83.678$; $p < 0.001$). More specifically, the mean area of the endpoint ellipses were the smallest at slower tempi, i.e., at ITI=1100 to 800 ms (Mean = 42.9 mm^2; SD = 23.7mm^2), with all other tempi being characterised by significantly larger errors. Spatial areas were the largest at faster tempi (from ITI=500 to 300 ms) and these results were significantly different from all other ITIs (Mean = 126.8 mm^2; SD = 73.96 mm^2).

Motor fluency. ANOVA conducted on the mean contact times revealed that the CTs were shorter with increasing tempi ($F(9; 225) = 31.14$; $p < 0.001$). Post Hoc tests revealed that the decrease in CT was linear with increasing tempi, with significant differences between the n^{th} trial and the trial (n+2). Nevertheless, no differences between neighbouring ITIs emerged at the slower tempi, i.e. between ITIs=1200 to 1000 ms for which the largest contact times were measured.

Overall, motor actions were precise in space and time at the slowest tempi (≥800 ms), less accurate in space but more fluent at intermediate tempi (at 700 and 600 ms of ITI), less precise in both space and time but much more fluent at faster tempi (from 500 to 300 ms of ITI).

Planning indicators.

Event-based timing. To note first is the fact that all AC-1 values were negative. Repeated ANOVAs on the AC-1 values showed that these values were significantly different in function of ITI ($F(9; 225) = 5.933$; $p < 0.001$). Post Hoc tests confirmed that the AC-1 values were the largest at slower tempi, i.e. for ITI=1100 to 900 ms of ITI (Mean = -0.28; SD = 0.15) and significantly smaller with increasing tempi, i.e. from ITI=800 to 400 ms (Mean = -0.17, SD = 0.18). The AC-1 value was finally the smallest at the fastest

ITI of 300 ms (Mean = -0.02, SD = 0.21). These results suggest that the timing mode was event-based for slow tempi (1200 to 900 ms) in this task.

Emergent timing. To note first that all AC-6 values were positive. Repeated ANOVAs on the AC-6 values revealed that these values were significantly different in functions of ITI ($F(9,225) = 8.524$; $p<0.001$). Post Hoc tests revealed that the AC-6 values were the smallest at slower tempi, i.e. for ITI=1200 to 900 ms (Mean = 0.08; SD = 0.15). At faster tempi (ITI=500 ms to 300 ms), the positive AC-6 values were the largest (Mean = 0.31, SD = 0.20) and not significantly different between each other. At intermediate tempi (from 800 to 600 ms), the AC-6 values were all significantly smaller than at least one of the faster ITIs and larger than at least one of the slower ITI. These results indicate that the timing mode became emergent at fast tempi of 500 to 300 ms of ITI.

Overall, these results suggests that the timing was event-based at slowest tempi (from 1200 to 900 ms), emergent at fastest tempi (500 to 300 ms) and in a transition phase at intermediate tempi (from 800 to 600 ms).

Neuropsychological tasks

Performance scores observed in the neuropsychological tasks are presented in table 1. $\chi 2$ tests revealed that performance scores were normally distributed across tasks.

Multiple Regression Analyses: ST vs. classical tasks

Beta coefficients and corresponding p-values are presented in table 2 for each regressor in function of each dependent variable. Results confirm our hypotheses: (1) small timing errors in the slow phase of the ST task predict short reaction times in the WM task, (2) short contact times in the ST-task predict larger number of inhibition error in the go-no-go task, (3) smaller are in the fast phase of the ST-task predict smaller switching cost in the letter-number task.

Table 1: Performance scores in the classic executive tasks

	N-back task (UPDATING)	Go-noGo task (INHIBITING)	Letter-number task (SWITCHING)	Normal FREQUENCY distribution
	Median RT (ms)	False Alarms	Switching Cost (ms)	
MEAN	576	1	126	
SD	158	1	89	
MIN	368	0	15	
MAX	928	3	371	
FREQUENCY > (+)1σ	6	0	4	4,08
FREQUENCY < (-)1σ	15	23	18	17,75
(-)1σ < FQ < (+)1σ	5	3	4	4,08
χ2 test (p-value)	0,467	0,051	0,996	

Table 2: Multiple regression analyses. Significant results are bolded.

SPATIAL TAPPING		NEUROPSYCHOLOGICAL TASKS					
		N-back (Updating)		Go-no-go (Inhibiting)		Letter-number (Switching)	
		Median RT (ms)		False Alarms		Switching cost (ms)	
		Beta Coeff.	p-value	Beta Coeff.	p-value	Beta Coeff.	p-value
Slow phase (1200 to 900 ms)	IRIerror	**0,484**	**0,026**	-0,160	0,480	0,080	0,687
	CT	0,021	0,931	-0,408	0,139	0,202	0,392
	AREA	0,066	0,804	0,434	0,144	0,389	0,134
Interm. Phase (800 to 600 ms)	IRIerror	0,504	0,156	-0,141	0,671	-0,127	0,718
	CT	0,173	0,413	**-0,474**	**0,026**	0,116	0,585
	AREA	-0,172	0,614	0,156	0,631	0,420	0,227
Fast phase (500 to 300 ms)	IRIerror	-0,043	0,843	-0,032	0,882	0,025	0,901
	CT	-0,029	0,883	-0,368	0,080	-0,064	0,736
	AREA	0,433	0,051	-0,200	0,358	**0,492**	**0,021**

Discussion

In this study, we asked whether a simple motor sequencing task could be used to assess the executive functions of planning described in the neuropsychological literature. This motor task was assumed to involve updating in working memory at slowest tempi, inhibiting at intermediate tempi, and switching at faster tempi. This hypothesis was tested by comparing performance scores in the spatial-tapping task to those scores obtained in three neuropsychological tasks selected to target each specific executive function. The findings reported here confirmed our working hypothesis. Indeed, in the slow phase of the spatial tapping task, results suggested that the motor actions were triggered through an internal representation of time intervals, with larger negative auto-correlations at slow tempi (from 900 to 1200 ms). To perform the task adequately, subjects were required to maintain actively in working memory the target time interval to produce, across the entire duration of the trial.

Regression analyses confirmed furthermore the existence of a relationship between these motor results and those performances obtained in a cognitive WM task, suggesting similar WM functions in the cognitive and in the motor domains. In the faster phase of the spatial-tapping task (from 500 to 300 ms), with actions becoming more circular, it was suggested that the action sequence was divided in two biomechanically distinct movements that compose the sequence, i.e., flexion vs. extension movement patterns. The cognitive goal in this case was then geared towards the need to coordinate smoothly the distinct movements composing the sequence towards a more global trajectory pattern that binds them together, here a circle. In circle drawing, this phenomena is actually measurable through the emergence of an anchor point that is a kinematic reduction in the timing and/or spatial variability at the point of transition between flexion/extension movements (Beek et al., 1992). It has been shown that the anchor point is effectively reduced through explicit anticipatory processes. Indeed, orienting the gaze in advance towards the anchor point significantly reduces the spatial variability observed at this point. In the same vain, flexing and extending the wrist in an anticipatory rhythmic fashion significantly reduces both the spatial and temporal errors respectively at the points of maximum flexion vs. extension related to the movement pathway (Roerdink et al., 2008). In the present results, we observed an anchor point within our circular trajectory at the point of maximal extension (upper left target); point in space at which smaller spatial variability was measured but only in the faster phase of the task, which confirms the role of emergent timing at fast tempi. In reference to the cognitive tests, our results revealed furthermore that the performances at fast tempi in the spatial tapping task were effectively related to smaller switching cost in a classical switching task, suggesting that switching between two biomechanical movements may be in fact controlled by those similar functions used for cognitive switching. Finally, in the intermediate phase of the spatial-tapping task, it was suggested that motor inhibition of a too fast transition from discrete to continuous actions entered into play to maintain high levels of spatial and timing accuracy in spite of the increase in temporal pressure. This hypothesis was confirmed here with longer contact times in the intermediate phase of the spatial-tapping task being significantly related with the ability to inhibit impulsive response in a classical go-no-go task.

In conclusion, we propose the spatial-tapping as a novel paradigm (1) to assess the executive functions in an easy and non-verbal context, (2) to gain a better understanding of the relationships between the distinct executive functions. This approach may be a promising way to reconsider cognitive strategy in broader context and offers a starting point for the study of the functional relationships between motor and cognitive control.

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