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Long-lasting effect of subliminal processes on cardiovascular responses and performance

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A B S T R A C T

Students were exposed to a priming task in which subliminal representations of the goal of studying were directly paired (priming-positive group) or not (priming group) to positive words. A control group without subliminal prime of the goal was added. Just after the priming task, students performed an easy or a difficult learning task based on their coursework. Participants in the priming-positive group performed better and had a stronger decrease of pulse transit time and pulse wave amplitude reactivity than participants of the two other groups, but only during the difficult condition. Results suggested that subliminal priming induces effortful behavior extending over twenty five minutes but only when the primes had been associated with visible positive words acting as a reward. These findings provide evidence that subliminal priming can have long-lasting effects on behaviors typical of daily life.

1. Introduction

Research on subliminal processing, which involves exposure to brief, masked stimuli that fail to be perceived consciously, has recently attracted considerable attention for it suggests that people's behavior can be influenced by factors of which they are not aware. Recently, several studies have suggested that even behavior associated with higher cognitive (Capa et al., 2011a; Lau and Passingham, 2007) and motivational functions (Gendolla and Silvestrini, 2010; Pessiglione et al., 2007) can be driven by subliminal processes. Because such effects never exceed a few seconds (e.g., Dupoux et al. 2008; Greenwald et al., 1996; Lu et al., 2005), there is widespread agreement that unconscious representations are short-lived (Dehaene and Naccache, 2001; Dehaene et al., 2006). Here, building on recent research on nonconscious goal pursuit conducted by Aarts et al. (2008a, 2008b) and Custers and Aarts (2007, 2010), we challenge this conclusion and show that subliminally activating a high-level goal such as the goal to study induces long-lasting effortful behavior (i.e., a greater cardiovascular reactivity related to resource mobilization and better performance) in students, extending over several minutes.

2. Nonconscious goal pursuit and resource mobilization

Several recent studies have investigated the effects that nonconscious processes exert on goal pursuit (Aarts et al., 2008b; Custers and Aarts, 2007). Aarts et al. (2008a) showed that participants dedicated more physical effort in a demanding force task over up to three seconds after exposure to subliminal word primes related to the goal of physical exertion when associated with visible positive words. This suggests that subliminal processes may directly induce a brief vigorous behavior toward the achievement of a goal. In another study, Capa et al. (2011b) extended these effects. Students exhibited higher cardiovascular response, after exposure to subliminal word primes related to the goal of studying associated with visible positive words, at the end of a learning task based on their coursework (i.e., after twenty minutes and over the last five minutes). More precisely, students showed a larger decrease of midfrequency band of heart rate variability and of the pulse transit time related to the β-adrenergic and α-adrenergic activity, respectively. These results segue well with the classical characteristics of goal pursuit behavior (Hockey, 1997; Kahneman, 1973): under difficult conditions, goal pursuit involves mobilization of mental resources to counteract the influence of difficulty across time on task and of fatigue.

3. The present research

In our previous study (Capa et al., 2011b), we failed to observe performance differences between groups. Further, the observed differences in cardiovascular reactivity appeared only at the end of the learning task. As a result, the cognitive and motivational mechanisms implicated could not be precisely identified. Moreover, it was not clear

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whether the observed differences of cardiovascular reactivity reflected mainly α and/or β-adrenergic activity. The present study sought to address these shortcomings. We first focus on the theory on resource mobilization and next on cardiovascular reactivity.

The present experiment was conducted on the idea that unconscious goal pursuit involves mobilization of mental resources and perseverance to attain it, extending over several minutes. To achieve this we exposed participants first to the primes and assessed then if this has effects on a subsequent learning task rather than integrating primes into a task to establish direct and short term effects—as frequently done in recent studies (Capa et al., 2011a; Gendolla and Silvestrini, 2010; Silvia et al., 2011). Based on the evaluative conditioning paradigm used by Aarts et al. (2008a, 2008b) and Custers and Aarts (2007), three groups of students were exposed to 100 trials of subliminal primes before performing an easy or a difficult learning task (see Fig. 1). For the *priming-positive group*, 50% of the trials directly associated subliminal priming of words related to the goal of studying with consciously visible positive words such as “important”. The other half of the trials combined different random letter strings with neutral words such as “around”. For the *priming group*, the goal to study was subliminally primed, but not directly paired with positive words—contrary to the priming-positive group. Fifty percent of trials linked words related to study with neutral words. The other half of the trials paired random letter strings with positive words. Note that in these two conditions participants were exposed to the same numbers of verbs, neutral and positive words. The only difference was that the associations between the primed goals were directly paired to positive words (priming-positive group) or not directly linked to positive words (priming group). Comparison between the priming-positive group and the priming group was designed to test the necessity of a direct association between the primed goal and the positive words. Based on the work of Aarts et al. (2008a, 2008b) and Custers and Aarts (2007), this direct association should signal that the accessible goal is worth pursuing and enhances resource mobilization when performing the difficult learning task, acting as a reward.

On the basis of the known characteristics of goal pursuit (Hockey, 1997; Kahneman, 1973) and a relevant theory of effort mobilization (Brehm and Self, 1989), when task difficulty is set to be very high and possible, individuals will strive to reach the highest performance level that is necessary to ensure goal attainment. In that case, effort mobilization is proportional to the peak of what an individual would be willing to do to succeed (Gendolla et al., 2008; Stewart et al., 2009). In the easy tasks, individuals mobilize energy as a function of their level of subjective difficulty and expend no more effort than necessary. Finally, to assess the effect of goal priming, a *control group* was included in which random letters strings were paired to both positive words and neutral words.

To test a mixed pattern of α and β-adrenergic activity during the learning task, resource mobilization was quantified by the reactivity of the cardiovascular system. The cardiovascular response pattern produced during an effortful task is predominantly characterized by β-adrenergic activity (Obrist, 1981; Wright, 1996) and may induce an increase of heart rate. However, heart rate is determined by both sympathetic and parasympathetic activation and responds only to effort mobilization when the sympathetic influence is stronger (Berntson et al., 1993). Askelrod et al. (1981) introduced spectral power analysis of heart rate variability to better differentiate the effects of sympathetic nervous system activity from those of parasympathetic nervous system activity. The sympathetic nervous system reacts rather slowly and its activity is reflected mainly in the midfrequency band ranging from 0.07 to 0.14 Hz. Fluctuations in this band are associated with short-term regulation of blood pressure which causes a resonance in the veins with a frequency of about 0.10 Hz (Mulder et al., 1995). Variability in this band has been shown to decrease during effortful mental tasks (e.g., Capa et al., 2008a, 2008b; Duschek et al., 2009; Fairclough et al., 2005). Moreover, previous reports found a correlation between midfrequency band of heart rate variability and pre-ejection period (Burgess et al., 2004)—the best non-invasive indicator of β-adrenergic impact on the heart (Sherwood et al., 1990)—and also systolic blood pressure (Mulder et al., 1995) which is mainly influenced by β-adrenergic activity. However, systolic blood pressure is partly influenced by peripheral resistance in the vasculature (Levick, 2003).

A mixed pattern of α and β-adrenergic sympathetic activity during effortful tasks has often been described (García-León et al., 2003; Kemper et al., 2008; Schneiderman and McCabe, 1989; Waldstein et al., 1997). To test this issue, we also focus on cardiovascular measures influenced by α-adrenergic activity: pulse transit time and pulse wave amplitude. Pulse transit time is the time taken for the pulse to travel between two arterial sites and is determined by factors influencing vascular distensibility, including α-adrenergic activity, although it may be susceptible to β-adrenergic activity as well (Contrada et al., 1995). Pulse transit time has been shown to shorten during difficult tasks (e.g., Duschek et al., 2009; Kemper et al., 2008; Tomaka et al., 1993). Finally, pulse wave amplitude is mainly influenced by the sympathetic nervous system (see Babchenko et al., 2001; for a review of pharmacological demonstrations) without influence of the parasympathetic nervous system and reflects mainly α-adrenergic activity (Gayton, 1977). A decrease of pulse wave amplitude (i.e., peripheral vasoconstriction) has been reported in performing difficult tasks (Iani et al., 2004; 2007).

4. Method

4.1. Participants

One hundred fourteen psychology students from the University of Liège were randomly assigned to one of 6 conditions in a 3 (Priming Task: priming positive group vs. priming group vs. control group) × 2 (Task Difficulty: easy learning task vs. difficult learning task) between-

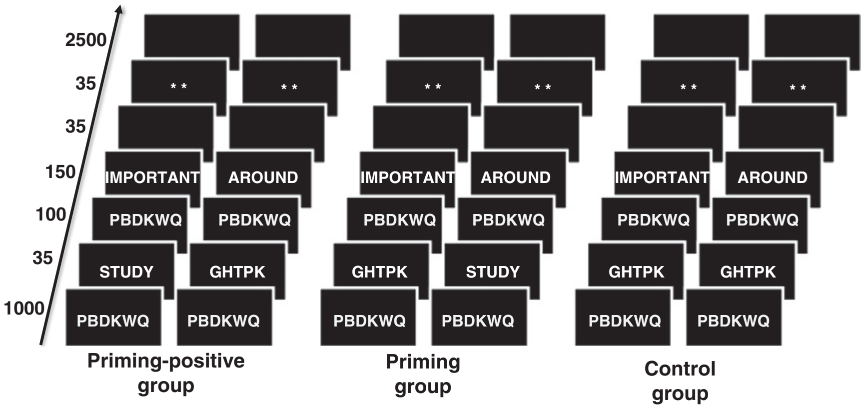

Fig. 1. Sequences of events used in the priming task, with durations in milliseconds.

participants factorial design (60 women, age range 18–27 years). Grade levels and participants' gender were counterbalanced across groups. All participants were right-handed.

4.2. Priming task

In a pilot study, 220 students selected five verbs (study, memorize, learn, cram for, and work) and five adjectives (important, necessary, deserving, indispensable, and essential) that describe the concept of studying on a Likert scale ranging from 1 (*completely disagree*) to 5 (*completely agree*) ($M=4.48$, $SD=.61$; $M=4.20$, $SD=.84$, respectively). Furthermore, participants were also asked to evaluate whether adverbs were related to a positive or a negative event on a Likert-type scale ranging from 1 (*completely disagree*) to 5 (*completely agree*). Five neutral adverbs (furthermore, around, next, also, and sometimes) were selected ($M=1.34$, $SD=.49$). On the basis of another pilot study ($N=24$), participants were asked to evaluate whether the five adjectives selected (e.g., important and necessary) were related to a positive event on a Likert-type scale ranging from 1 (*completely disagree*) to 5 (*completely agree*) ($M=4.01$, $SD=.86$). These words were used in the priming task.

The priming task was composed of 100 trials. Each trial lasted 38.55 s and started with a random letter string followed—according to the groups—by a subliminal prime word or by a random letter string (Fig. 1). A random letter string then appeared again, followed by a visible word. The word was a positive adjective or a neutral adverb. Next, one, two, or no dot, were presented without pre and post-mask during 35 ms. Without pre and post-mask, the dots could quite easily be detected. Participants were instructed to press the key 1 or 2 of a standard keyboard, if they had seen one or two dots, respectively, and to refrain from responses if there was no dot. After a 2500 ms blank interval, a new trial started. This procedure ensured that participants paid attention to the words during the task without being aware of the prime. The cognitive processes at work in masked priming experiments are dependent of attention (Naccache et al., 2002). The priming task was presented on an 85-Hz CRT screen.

4.3. Learning task

Four members of the teaching staff from the University of Liège constructed sentences. They extracted ten sentences from 40 specific psychology courses. For the social psychology course, sentences such as: “When an event occurs, the average person spontaneously makes causal: inferences” or “Attribution theory is concerned with how individuals interpret: events” were constructed. The four members of the teaching staff used criteria such as number of words, level of clarity and difficulty, and importance of the topic to construct the sentences.

The task was composed of 40 trials and lasted 26 min (39.6 s by trial). The task started with a fixation cross, immediately followed by four sentences in the easy condition (5875 ms by sentence) and ten sentences in the difficult condition (2350 ms by sentence) (see Fig. 2). For each condition, two sentences among those presented appeared again with the last word missing instead of one in our previous study (Capa et al., 2011b). The goal was to increase reliability of the behavioral measure. Participants were instructed to select the correct last words in two separate four-choice recognition sets. After each response, participants received feedback. This feedback concerned the response speed and the number of errors. Only the reaction times of the correct responses were examined. Participants were instructed to react as quickly as possible without making errors.

Furthermore, a starting signal was presented at the beginning of each trial (1500 ms). In the easy learning task, a fixation cross or a square appeared. In the difficult condition, a fixation cross, a square, or a triangle was presented. Participants were instructed to count the number of square in the easy condition and the number of square and of triangle in the difficult condition while carrying out the learning task. At the end of the learning task, participants indicated the correct numbers (12 squares in the easy condition, and 8 squares and 14 triangles in the difficult condition). The dual-task condition was used for a main reason. Mulder et al. (1995), using a similar task, found no effect of task engagement on cardiovascular reactivity under single-task condition. Effects on cardiovascular reactivity were only evident under dual-task conditions (i.e., visual memory search task and counting task).

4.4. Subjective measures

Participants filled out two subjective difficulty scales. The first was the Task Load indeX (TLX; Hart and Staveland, 1988), which involves six dimensions (i.e., mental demand, physical demand, temporal demand, performance, effort, and frustration). Participants indicated a score from 1 to 10 on each dimension. Next, the weighting procedure required the participants to choose which dimension was more relevant to workload across all pairs of six dimensions. This procedure was used to combine the six dimension ratings into a single global score of subjective difficulty. We used also the scale of Eccles and Wigfield (1995) in order to construct four items of perceived difficulty. One such example is the following: “How hard is this task for you?”. Participants responded on a scale ranging from 1 (*very easy*) to 5 (*very difficult*).

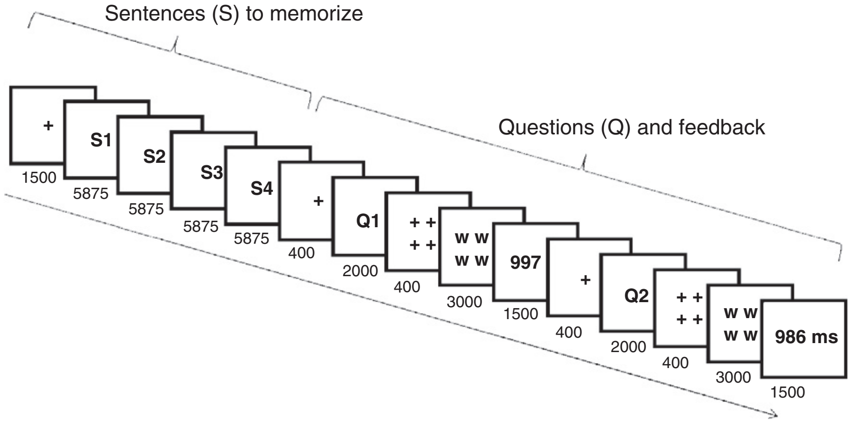

Fig. 2. Successive screens displayed in one trial of the easy learning task, with durations in milliseconds. At the beginning of each trial, a fixation cross appeared. This was immediately followed by four sentences (S) in the easy condition (5875 ms by sentence) and ten sentences in the difficult condition (2350 ms by sentence). For each condition, two sentences (Q) were presented again with the last word missing. Participants selected the correct last word (w) in a four-choice recognition set and received knowledge of result concerning the speed in milliseconds of their response.

Furthermore, a high frequency of pursuit of the goal to study may influence investment and perseverance to attain this goal (Custers and Aarts, 2007). Therefore, to ensure that the groups were comparable, we also assessed the frequency with which the goal to study was pursued over time. Participants were asked four questions such as “How often do you think about working your courses?” on a 5-point scale from *never* to *very often*.

4.5. Cardiovascular measures

An electrocardiogram (ECG) was recorded using the Psylab Model BIO2 isolated AC amplifier (Contact Precision Instruments, London, UK). Three 16-mm Ag/AgCl electrodes (Red Dot, 3M) were placed in a modified Lead II position. Peripheral pulse signals were recorded using the Psylab Model PPA2 peripheral pulse amplifier with a Psylab (Model PT1) photoplethysmograph transducer placed on the finger of participants' non-dominant hand. The ECG and peripheral pulse signals were continuously monitored and digitized online (500 Hz). Data were visually inspected. Those considered as artifactual were manually replaced by interpolated or extrapolated data (mean of the three values preceding). As a guard against artifact, we omitted interpulse and R–R intervals lower than 500 ms and higher than 1500 ms. The amount of abnormal data was less than 2%.

Four parameters were derived from the cardiovascular recordings: heart rate, midfrequency band, pulse transit time, and pulse wave volume. Heart rate (beats per minute [bpm]) was obtained from R–R intervals of the ECG data. In accordance with the Task Force (1996) recommendations, we selected suitable series of 256 R–R intervals of the ECG data for spectral analysis of heart rate variability. The fast Fourier transform spectra analysis was calculated from this 256 R–R interval with HRV analysis software 1.1 for Windows (Niskanen et al., 2004). We used fluctuations in the midfrequency band ranging from 0.07 to 0.14 Hz (Mulder et al., 1995). The spectral power values of the midfrequency band were in absolute values of power in milliseconds squared. To approach normal distribution of the data for statistical analysis, the spectral power values were transformed into logarithmic values. Pulse transit time, the interval in milliseconds between the ECG R-wave and the onset of the finger pulse wave, was registered using two Psylab Interval Timers that were linked together. Finally, pulse wave amplitude was continuously measured using data of the photoplethysmograph. The Psylab device measures the pressure changes accompanying the blood volume pulse, a fast component of the synchronous changes amplitude in the blood volume with each heart beat, and translates them into pulse amplitude values in millivolts.

4.6. Procedure and setting

The experiment took place in a sound-attenuated, temperature-constant, electrically shielded recording room. After participants had read and signed a consent form, the experimenter installed the photoplethysmograph transducer and the electrodes. This stage was followed by a 10-min baseline recording. Participants were instructed to rest quietly. Next, participants performed a training session of the learning task (2 blocks of 5 trials). Then, participants performed the priming task. Immediately after completion of the learning task, participants filled out the TLX, the perceived difficulty scale, and the scale concerning the frequency with which the goal to study was pursued. Finally, each participant performed a forced-choice test to detect prime visibility.

4.7. Data analysis

For the priming and learning tasks, behavioral and subjective data were submitted to explorative 3 (Priming Task: priming positive group vs. priming group vs. control group)×2 (Task Difficulty: easy learning task vs. difficult learning task) ANOVAs between groups. Post hoc comparisons were conducted using one-way ANOVAs between groups. Cardiovascular reactivity scores were calculated by subtracting values from the baseline period from the values of the priming task or the learning task. Concerning cardiovascular reactivity scores, we tested our theory-based predictions with contrast analyses which are the appropriate and most powerful statistical tool to test predicted interactions in experimental designs (Rosenthal and Rosnow, 1985). We anticipated that participants in the priming-positive group (contrast weight = +5) had a stronger cardiovascular reactivity than participants of the priming (contrast weight = −1) and control (contrast weight = −1) groups, but only during the difficult condition. We anticipated low cardiovascular reactivity in the easy condition for each group (contrast weight = −1). Based on previous results (Capa et al., 2011b), we did not anticipate reactivity during the priming task. This should result in contrast × time interaction effects on cardiovascular reactivity. In the case of significant interaction, we ran separate contrast analyses of cardiovascular reactivity during the priming task and the learning task.

5. Results

5.1. Behavior

Behavioral data of the priming task are presented in Table 1 and were examined with two-way ANOVAs (3 priming task×2 task difficulty). Analyses of mean reaction times and the arcsinus-transformed proportion of errors revealed no significant difference between groups (all $ps > .25$). Behavioral data of the learning task are presented in Table 2. Data were examined with two-way ANOVAs (3 priming task×2 task difficulty). Results show a main effect of task difficulty, with faster reaction times in the easy condition ($M = 1284.02$, $SD = 105.23$) compared to the difficult condition ($M = 1594.02$, $SD = 185.11$), reflecting a successful manipulation of task difficulty, $F(1,108) = 129.65$, $p = .001$, $\eta^2_p = .55$, and a marginal tendency of priming task, $F(2,108) = 2.89$, $p = .06$, $\eta^2_p = .05$. Participants of the priming-positive group ($M = 1395.36$, $SD = 165.72$) tended to perform faster than participants of the priming and control groups ($M = 1447.47$, $SD = 214.88$, and $M = 1474.22$, $SD = 256.33$, respectively). Most relevant, the 3×2 ANOVA revealed a significant interaction between priming task and task difficulty on the mean reaction times, $F(2,108) = 3.20$, $p < .04$, $\eta^2_p = .06$ (Fig. 3). Participants of the priming-positive group had faster mean reaction times than participants of the priming and control groups but only during the difficult task. This was confirmed by complementary one-way ANOVAs. In the difficult condition, participants of the priming-positive group had faster mean reaction times than participants of

Table 1
Means and standard deviations of the behavioral and cardiovascular data, as a function of groups, for the priming task.

	Priming-positive		Priming		Control	
	Easy	Difficult	Easy	Difficult	Easy	Difficult
RT	531.22	530.08	531.15	549.53	537.15	562.18
	(71.76)	(64.09)	(54.50)	(49.61)	(54.50)	(89.19)
ER	.34	.35	.36	.34	.35	.34
	(.08)	(.15)	(.11)	(.07)	(.09)	(.05)
HR	76.71	73.51	75.97	75.75	80.16	72.77
	(6.16)	(7.00)	(15.95)	(9.44)	(19.36)	(6.50)
MFB	472.87	396.10	800.24	529.25	682.23	509.95
	(397.58)	(322.21)	(743.00)	(577.27)	(477.48)	(422.28)
PTT	180.51	176.24	174.18	177.70	173.43	180.61
	(9.96)	(14.81)	(13.78)	(14.57)	(12.82)	(18.49)
PWA	44.61	38.58	44.00	44.28	43.86	39.27
	(26.42)	(19.71)	(20.17)	(15.70)	(19.03)	(16.93)

Note: Standard deviations are in parentheses. RT = reaction time; ER = error rate; HR = heart rate; MFB = midfrequency band; PTT = pulse transit time; PWA = pulse wave amplitude.

Table 2
Means and standard deviations of the subjective and the behavioral as a function of groups, for the learning task.

	Priming-positive		Priming		Control	
	Easy	Difficult	Easy	Difficult	Easy	Difficult
TLX	5.10	8.36	5.06	8.17	5.27	8.15
	(1.30)	(.82)	(1.00)	(1.33)	(.99)	(1.03)
PD	11.11	16.11	11.32	16.05	10.79	15.89
	(2.21)	(2.18)	(2.91)	(2.59)	(1.65)	(2.28)
FGP	15.95	15.47	15.58	14.89	15.58	16.11
	(3.52)	(2.89)	(3.19)	(2.05)	(1.02)	(2.11)
RT	1287.63	1503.09	1278.87	1616.07	1285.54	1662.91
	(97.78)	(149.81)	(116.91)	(145.73)	(105.98)	(220.62)
ERLT	.39	.74	.41	.77	.41	.72
	(.20)	(.17)	(.22)	(.16)	(.22)	(.19)
ERCS	.26	.62	.30	.60	.33	.55
	(.33)	(.42)	(.30)	(.56)	(.35)	(.35)
ERCT	–	.45	–	.51	–	.53
	–	(.48)	–	(.51)	–	(.43)

Note. Standard deviations are in parentheses. TLX = task load index; PD = perceived difficulty; FGP = frequency of goal pursuit; RT = reaction time; ERLT = error rate in learning task; ERCS = error rate in counting the squares; ERCT = error rate in counting the triangles.

the priming group, $F(1,36) = 5.55$, $p < .02$, $\eta^2_p = .13$, and of the control group, $F(1,36) = 6.82$, $p < .01$, $\eta^2_p = .16$. No significant difference emerged between the priming and control groups ($p = .45$) in the difficult condition and also between groups in the easy condition (all $ps > .80$). Note that the same pattern of result was obtained for the cardiovascular reactivity scores. In order to detect potential changes in speed–accuracy trade-off between groups, the arcsinus-transformed proportion of errors in the learning task, in the counting task of squares and of triangles were examined with separate ANOVAs (3 priming task × 2 task difficulty). Only a higher proportion of errors in the difficult task compared to the easy task emerged in the learning task ($M = .74$, $SD = .17$, and $M = .40$, $SD = .21$, respectively), in the counting task of squares ($M = .59$, $SD = .45$, and $M = .30$, $SD = .32$, respectively) and of triangles ($M = .50$, $SD = .47$, and $M = .30$, $SD = .42$, respectively), reflecting a successful manipulation of task difficulty, (all $ps < .02$ and $\eta^2_p s > .05$). No other effect was found (all $ps > .76$).

5.2. Subjective data

Subjective data of the learning task are presented in Table 2. A main effect of task difficulty was found. Both TLX and perceived difficulty scores were higher in the difficult condition ($M = 8.23$, $SD = 1.06$, and $M = 16.02$, $SD = 2.32$, respectively) compared to the easy condition ($M = 5.15$, $SD = 1.09$, and $M = 11.07$, $SD = 2.28$, respectively), reflecting a successful task difficulty manipulation, $F(1,108) = 127.78$, $p < .001$, $\eta^2_p = .54$, and $F(1,108) = 226.43$, $p < .001$, $\eta^2_p = .68$, respectively. No other effect was significant. Moreover, analysis of the frequency of goal pursuit scores revealed no significant effect (all $ps > .55$).

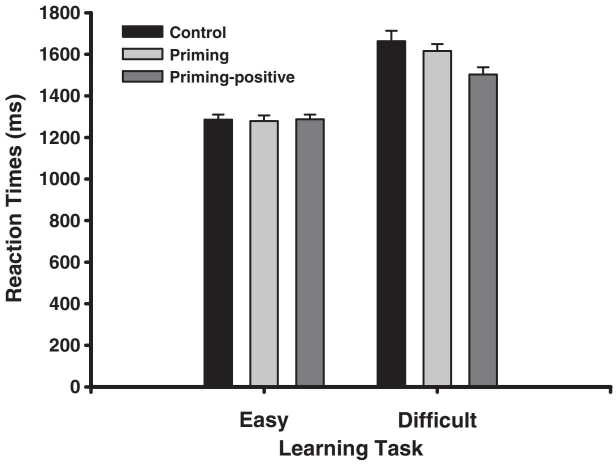

Fig. 3. Mean reaction times as a function of the priming-positive, priming, and control groups and the level of difficulty of the learning task.

Table 3
Means and standard deviations of the baseline of the cardiovascular measures as a function of groups.

	Priming-positive		Priming		Control	
	Easy	Difficult	Easy	Difficult	Easy	Difficult
HR	72.60	69.10	71.89	72.57	74.98	68.73
	(9.04)	(7.86)	(17.86)	(10.47)	(17.51)	(6.02)
MFB	466.33	441.89	398.39	772.96	490.90	351.32
	(714.32)	(706.48)	(305.04)	(1367.11)	(524.76)	(231.23)
PTT	187.53	183.79	180.54	183.46	179.89	187.23
	(12.53)	(14.58)	(15.01)	(14.66)	(9.58)	(17.89)
PWA	61.91	59.35	63.36	59.76	57.73	53.21
	(35.49)	(30.86)	(23.06)	(23.88)	(23.58)	(25.28)

Note: Standard deviations are in parentheses. HR = heart rate; MFB = midfrequency band; PTT = pulse transit time; PWA = pulse wave amplitude.

5.3. Cardiovascular baseline and reactivity

Prior to the main analyses, for each cardiovascular measure, we examined whether groups differed between rest periods (Table 3) with a 3 (Priming Task: priming positive group vs. priming group vs. control group) × 2 (Task Difficulty: easy learning task vs. difficult learning task) ANOVA. No difference of cardiovascular baseline values between groups was found (all $ps > .19$). Moreover, preliminary 3 (Priming Task: priming positive group vs. priming group vs. control group) × 2 (Task Difficulty: easy learning task vs. difficult learning task) between persons ANCOVAs found that baseline values for each cardiovascular measure (i.e., heart rate, midfrequency band, pulse transit time, and pulse wave amplitude) were significantly related to their respective reactivity scores in the priming task and also in the learning task (all $ps < .01$ and $\eta^2_p s > .05$). Complementary, one-way ANCOVAs found that baseline values for each cardiovascular measure were significantly related to their respective reactivity scores for each group (all $ps < .04$ and $\eta^2_p s > .05$). Consequently for each cardiovascular variable, we adjusted the reactivity scores with respect to the baseline in the further analyses (Llabre et al., 1991).

5.3.1. Cardiovascular reactivity

Data of cardiovascular activity for the priming task and the learning task (heart rate, midfrequency band, pulse transit time, and pulse wave amplitude) are presented in Tables 1 and 4, respectively. The a priori contrast × time ANOVA revealed no significant effect for heart rate reactivity and midfrequency band reactivity (all $ps < .30$).

Table 4
Means and standard deviations of the cardiovascular data, as a function of groups, for the learning task.

	Priming-positive		Priming		Control	
	Easy	Difficult	Easy	Difficult	Easy	Difficult
HR	77.13	75.99	77.03	76.55	80.97	74.32
	(6.91)	(7.75)	(18.24)	(10.50)	(15.01)	(6.61)
MFB	810.62	782.41	545.42	1431.89	743.82	462.77
	(396.86)	(362.99)	(531.83)	(458.46)	(452.59)	(503.58)
PTT	182.06	171.30	175.22	175.92	174.41	180.04
	(7.87)	(14.26)	(12.60)	(14.96)	(8.80)	(17.01)
PWA	40.07	13.21	42.05	30.53	44.01	30.04
	(20.35)	(6.14)	(18.78)	(15.34)	(17.32)	(17.47)

Note. Standard deviations are in parentheses. HR = heart rate; MFB = midfrequency band; PTT = pulse transit time; PWA = pulse wave amplitude.

5.3.2. Pulse transit time reactivity

The contrast × time interaction ANOVA revealed a significant main effect of time, $F(1,107) = 7.92$, $p < .006$, $\eta^2_p = .07$, reflecting stronger pulse transit time reactivity during the learning task than during the priming tasks ($M = -7.23$, $SD = 7.12$, and $M = -6.63$, $SD = 6.65$, respectively), a significant contrast main effect, $F(1,107) = 4.14$, $p < .04$, $\eta^2_p = .05$, and the expected significant contrast × time interaction, $F(1,107) = 10.87$, $p < .001$, $\eta^2_p = .11$ (Fig. 4). We further explored this interaction with separate contrast analysis for the priming task and learning task periods. As anticipated, the contrast was not significant during the priming task ($p = .43$). However, it was significant during the learning task, $F(1,107) = 10.02$, $p < .002$, $\eta^2_p = .11$. The residual of the contrast was not significant indicating that no significant variance remained unexplained ($F < 1$). Participants of the priming positive groups had a stronger decrease of the pulse transit time reactivity than participants of the priming and control groups but only during the difficult task. In the difficult condition, two complementary one-way ANOVAs revealed that participants of the priming-positive group had a stronger decrease of the pulse transit time reactivity than participants of the priming group, $F(1,35) = 4.78$, $p < .04$, $\eta^2_p = .12$, and of the control group, $F(1,35) = 6.96$, $p < .01$, $\eta^2_p = .17$. The difference between the priming and control groups was not significant ($p = .73$). Moreover, in the easy condition, no difference between groups was significant (all $ps > .09$).

5.3.3. Pulse wave amplitude reactivity

The contrast × time interaction ANOVA revealed a significant main effect of time, $F(1,107) = 5.60$, $p < .02$, $\eta^2_p = .07$, reflecting stronger pulse wave amplitude reactivity during the learning task than during the priming tasks ($M = -25.90$, $SD = 24.83$, and $M = -16.80$, $SD = 15.62$, respectively), a significant contrast main effect, $F(1,107) = 27.95$, $p < .0001$, $\eta^2_p = .21$, and the expected significant contrast × time interaction, $F(1,107) = 33.80$, $p < .0001$, $\eta^2_p = .24$ (Fig. 5). We further explored this interaction with separate contrast analysis for the priming task and learning task periods. As anticipated, the contrast was not significant during the priming task ($p = .10$). However, it was significant during the learning task, $F(1,107) = 47.07$, $p < .0001$, $\eta^2_p = .31$. The residual of the contrast was not significant indicating that no significant variance remained unexplained ($F < 1$). Complementary one-way ANOVAs were carried out. In the difficult condition, the priming-positive group had a stronger decrease of the pulse wave amplitude reactivity than the priming group, $F(1,35) = 4.78$, $p < .04$, $\eta^2_p = .12$, and the control group, $F(1,35) = 6.96$, $p < .01$, $\eta^2_p = .17$. No significant difference between the priming and control groups was found ($p = .73$). In the easy condition, there was no significant difference between groups (all $ps > 55$).

5.3.4. Complementary analyses

We computed physiological reactivity scores for 10 successive periods of the learning task and of the priming task. For the learning task, contrary to a previous study (Capa et al., 2011b), no effect across time on task for each cardiovascular measure has been found (all $ps > .65$). Task demand of the learning difficult task was increased compared to the previous study (Capa et al., 2011b) (i.e., sentences duration was reduced from 2600 ms to 2350 ms and complexity of the sentences was increased). The goal was to induce a greater cardiovascular reactivity

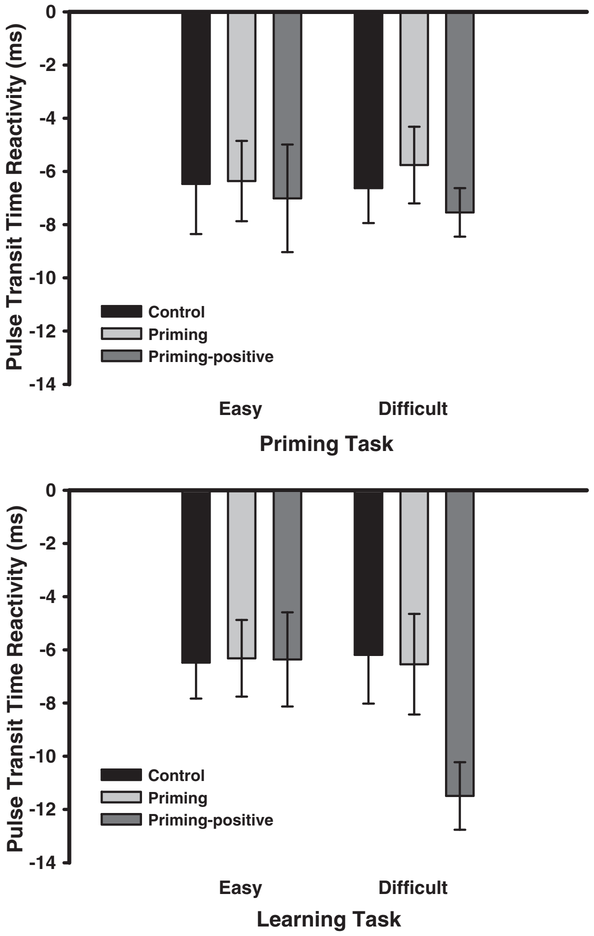

Fig. 4. Means and standard errors of pulse transit time reactivity during the priming task (top panel) and the learning task (bottom panel).

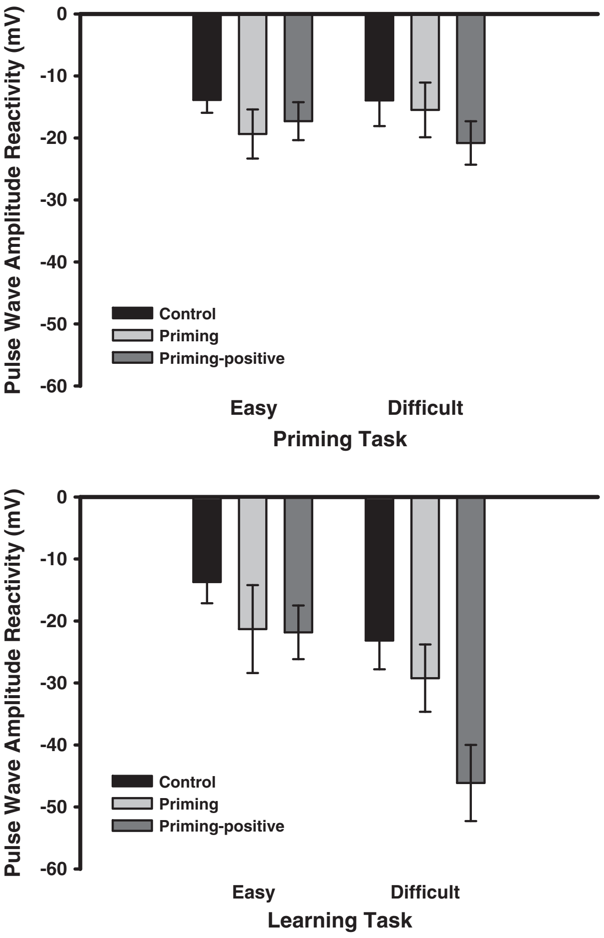

Fig. 5. Means and standard errors of pulse wave amplitude reactivity during the priming task (top panel) and the learning task (bottom panel).

from the beginning to the end of the task and not across time on task and fatigue as in the previous experiment (Capa et al., 2011b). For the priming task, for each cardiovascular measure, we computed physiological reactivity scores for 10 successive periods. As in a previous study (Capa et al., 2011b), no effect across time on task for the cardiovascular measures has been found (all $ps > .67$). These results suggest that the different conditions of priming themselves did probably not involve resource mobilization. In brief, during the priming task, there was no difference of cardiovascular reactivity between groups, suggesting that the different conditions of priming themselves did probably not involve mobilization of effort.

5.4. Perception of the prime

After the learning task, each participant performed a forced-choice test. They were fully informed that a verb or a random letter string was briefly presented between the pre-mask and post-mask and that they were subjected to the priming and priming-positive treatments. The prime visibility task was composed of 100 trials. At the end of each trial, a pair of choices was presented (i.e., the verbs related to study or the random letter strings). Participants were told that only response accuracy, not response speed was important and that the pair of choices would remain on the screen until a response was made. For each group, Student's t-tests revealed no significant difference between the mean percentage of correct responses ($M = 51.05$, $SD = 5.59$) and chance ($M = 50$), (all $ps > .16$). In addition, a d' score was calculated for each participant ($M = .05$, $SD = .28$). For each group, Student's t-tests revealed no significant difference between d' scores and zero (all $ps > .16$).

6. Discussion

In the present study, the long-lasting effect of subliminal processes on effort mobilization, suggested by the work of Aarts et al. (2008a, 2008b) and Custers and Aarts (2007) and a previous study of Capa et al. (2011b), was investigated using behavioral, subjective, and physiological measures. The results showed that activating the goal of studying through subliminal priming induced students to mobilize resources to learn coursework, but only when the goal is co-activated with positive words and when students performed a difficult learning task.

6.1. Behavioral and subjective results

Performance deterioration (i.e., mean reaction time) was less important for the priming-positive group than for the priming and control groups during the difficult learning task condition. Analyses of the proportion of errors in the learning task and counting tasks revealed no significant difference between groups. We can thus conclude that there was no speed–accuracy trade-off between groups. The better performance shown by participants of the priming-positive group compared to participants of the priming and control groups suggests a higher resource mobilization. Another possibility is that participants of the priming-positive group had a greater ability to perform the learning task. Correspondingly, for the same level of mobilized resources, participants of the priming-positive group showed better performance than participants of the priming and control groups. No evidence for this hypothesis was found. Although zero-effects do not allow firm conclusions, we note that no group difference was found for the perceived difficulty scale, the task load index, and the frequency of goal pursuit scale, suggesting no between-group difference in the ability and in the level of expertise to perform the learning task.

6.2. Cardiovascular reactivity

The better performance shown by participants of the priming-positive group compared to participants of the priming and control groups can be interpreted as a greater mobilization of resources because priming-positive participants had a stronger decrease of pulse wave amplitude and pulse transit time responses than participants of the two other groups when they performed the difficult learning task. A decrease in pulse wave amplitude is caused mainly by the α-adrenergic activity. Our findings thus extend Obrist's (1981) suggestion that effort is related exclusively to β-adrenergic activity by showing the importance of α-adrenergic activity. This result accords well with studies on cardiovascular reactivity showing α-adrenergic activity in an incentive-related performance situation (Waldstein et al., 1997), a vigilance task (Schneiderman and McCabe, 1989), a sustained attention task (Kemper et al., 2008), and a memory task (Iani et al., 2004, 2007). In line with these studies, the present task exhibited a context for α-adrenergic activity related to resource mobilization. Complementarily, pulse transit time reactivity showed the same pattern. However, pulse transit is determined mainly by α-adrenergic activity, although it may be susceptible to β-adrenergic activity as well (Contrada et al., 1995). Previous studies showed correlation between pulse transit time and pre-ejection period and also systolic blood pressure (Payne et al., 2006). Pre-ejection period is the best non-invasive indicator of β-adrenergic impact on the heart (Sherwood et al., 1990). Systolic blood pressure is mainly influenced by β-adrenergic activity and partly by peripheral resistance in the vasculature (Levick, 2003). In the last 10 years evidence supporting these two cardiovascular measures as a marker of resource investment has accumulated (Wright and Gendolla, 2011). The significant contribution of pre-ejection period and systolic blood pressure to pulse transit time means that pulse transit time should not be used as a marker of purely α-adrenergic activity (Payne et al., 2006).

An open question is whether there was a difference of β-adrenergic activity between groups in the present study. No effect on heart rate and midfrequency band responses was found. It is a common finding that heart rate, both sympathetically and parasympathetically mediated, is not systematically sensitive to effort investment (Wright, 1996). Moreover, the midfrequency band is a good index of β-adrenergic activity under the condition that this band is not influenced by respiratory activity (Althaus et al., 1998). To actually account for the impact of respiratory processes on heart rate variability, blood pressure and respiration must be recorded simultaneously with the heart rate signal. In the present study we did not control for respiratory-related variations in heart rate variability. Moreover, cardiovascular literature on autonomic mediation of midfrequency band is controversial. Some authors, notably Mulder et al. (1995) and Malliani et al. (1991), have argued that midfrequency band reflects mainly fluctuations of sympathetic activity. However, others authors have argued that midfrequency band reflects fluctuations of both sympathetic and parasympathetic branches (Berntson et al., 1993). Future research should aim to test our hypotheses of a mixed pattern of α and β-adrenergic activity more precisely by considering more reliable and sensitive cardiovascular measures of β-adrenergic activity, such as the pre-ejection period (Richter, 2010) and systolic blood pressure (Wright, 1996).

6.3. How does nonconscious goal pursuit affect effort mobilization?

One interpretation of the results is that the priming-positive condition has activated vigorous behavior by increasing the importance of goal attainment and the maximally justified effort. This upper limit of what an individual would be willing to do to succeed is determined by variables related to the importance of success (Brehm and Self, 1989; Gendolla et al., 2008, Stewart et al., 2009). In the difficult learning task condition, participants invested the maximally justified effort to achieve it. Participants of the priming-positive group, therefore, invested more effort than the other participants. However, in the easy learning task condition, participants mobilized no more energy than necessary to achieve the goal. This interpretation accords well with the fact that during the priming task—a relatively easy task to achieve—no difference of performance and of cardiovascular reactivity between groups was observed, suggesting that the priming task probably does not affect cardiovascular reactivity and performance directly but rather indirectly, that is, by modulating them through setting the extent of effort necessary to succeed.

6.4. Long-lasting effect of subliminal processes

The short-lived nature of unconscious representations is generally admitted (Dehaene and Naccache, 2001; Dehaene et al., 2006). For instance, experiments that have manipulated stimulus onset asynchrony between prime and target (typically, on the order of 50–150 ms) show that the amount of priming drops sharply to a non-significant value within a few hundreds of milliseconds (e.g., Dupoux et al., 2008; Greenwald et al., 1996; Naccache et al., 2002; Lu et al. 2005). Why it is the case that participants of the priming-positive group, in the present study, performed better and had a stronger cardiovascular reactivity related to effort mobilization extending over twenty five minutes whereas other studies that showed short term effects is open to argument. We surmise that this difference stems from the fact that in the current study, contrary to several studies in cognitive sciences, we used subliminal stimuli that are intrinsically related to people's goals and motivation. Recent studies used subliminal stimuli related to people's goals and motivation (Capa et al., 2011a; Gendolla and Silvestrini, 2010; Silvia et al., 2011) but were designed to show short term mobilization of effort (i.e., several seconds) during task performance.

Very few studies have reported long-lasting effects of subliminal processes. Pessiglione et al. (2008) asked participants, just after seeing a mask contextual cue flashed, to choose to press or not press a response key and subsequently observe the outcome (i.e., a cumulative earning score presented at the end of each trial). Three cues were used, one cue was rewarding (+£1), one was punishing (−£1), and the last was neutral (£0). At the end of the task, cues were presented to the participants and they rated them in order of preferences. Ratings were higher for reward compared to punishment cues, suggesting a learning of the affective values of subliminal cues and, consequently, long-lasting effects of subliminal processes. An important question concerns why the study of Pessiglione et al. (2008) and the present study are suggestive that subliminal stimuli can have a long-lasting effect, whereas many other studies are not. We surmise that this difference stems from the fact that in these studies a direct association between subliminal stimuli and positive valence was used and seems to be a key requirement for the occurrence of long-lasting non-conscious effects.

Two other interesting studies have demonstrated effects of subliminal processes extending over few minutes (Albarracín et al., 2008; Shah and Kruglanski, 2003). In these two studies, prime duration was of 50-ms. Unconscious and preconscious stimuli (generally under and above 50-ms of duration, respectively) frequently displayed a differential pattern of behavioral response and differential origins of the behavioral response (Dehaene et al., 2006; Van den Bussche et al., 2010). Moreover, in these two studies, participants did not perform a forced-choice test after each trial concerning perception of the primes. In brief, these results could be interpreted, at least in part, in terms of a preconscious bias that could not be ruled out in the absence of a force choice test after each trial.

In conclusion, the present findings show that subliminal priming can induce effortful behavior during over twenty five minutes only when the task difficulty is high. Therefore, the short-time impact of unconscious stimulation must be reconsidered.

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