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Practice-induced and sequential modulations in the Simon task: evidence from pupil dilation

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ABSTRACT

Recent evidence showed that pupil dilation (PD) reflects modulations in the magnitude of the Simon interference effect due to correspondence sequence. In the present study we used this measure to assess whether these modulations, thought to result from cognitive control mechanisms, are influenced by prior practice with an incompatible stimulus-response (S-R) mapping. To this end, PD and reaction times (RTs) were recorded while participants performed a Simon task before and after executing a spatially incompatible practice. The sequential analysis revealed that PD mirrored the conflict-adaptation pattern observed in RTs. Crucially, sequential modulations were not affected by prior practice. These findings support the view that the modulations of the Simon effect due to prior practice and those due to correspondence sequence result from two different mechanisms, and suggest that PD can help to better understand the mechanisms underlying response selection and cognitive control in the Simon task.

1. Introduction

Early works suggested that pupil dilation (PD) might be the most reliable autonomic physiological indicator of mental effort (e.g., Colman and Paivio, 1969; Kahneman, 1973; Tursky et al., 1969) with pupil diameter consistently showing an increase in response to increased task demands (Loewenfeld, 1993; for a review see Beatty, 1982; Beatty and Lucero-Wagoner, 2000). Starting from these early works, the task-evoked pupillary response has been taken into account as an index of cognitive load in a series of studies (see Goldinger and Papesh, 2012; Laeng et al., 2012; Sirois and Brisson, 2014, for reviews) investigating mental imagery (e.g., Laeng and Sulutvedt, 2014; D'Ascenzo et al., 2014), language processing (e.g., Zekveld and Kramer, 2014), memory (e.g., Wu et al., 2012) and attention (e.g., Alnæs et al., 2014).

Furthermore, in recent studies assessing the interference between stimuli and responses in the Stroop task, larger PD was found during either correct conflictual trials (i.e., incompatible vs. compatible stimuli; Laeng et al., 2011) or after post-conflictual errors (Critchley et al., 2005; Wessel et al., 2011). These conflict-related PDs have been reported by several studies not only using the Stroop task (Brown et al., 1999; Siegle et al., 2004; Siegle et al., 2008; Laeng et al., 2011), but also in studies using the Eriksen flanker task (van Bochove et al., 2013; Wendt et al., 2014).

More recently, van Steenbergen and Band (2013) reported conflict-related PDs using another widely used conflict-inducing task, the Simon task. In the typical Simon task participants are required to respond to a non-spatial feature (e.g., color) of stimuli randomly appearing on the right or on the left of fixation, by pressing a spatially defined response (e.g., a left or right response key). Although stimulus position is task-irrelevant, faster and more accurate responses are observed when stimulus position and response position spatially correspond (i.e., corresponding condition) compared to when they do not correspond (i.e., noncorresponding condition) (Simon and Rudell, 1967; see Rubichi et al., 2006; Proctor and Vu, 2006, for reviews). The difference between corresponding and noncorresponding trials, termed Simon effect, is usually explained by means of dual-route models that distinguish between direct or automatic and indirect or controlled processes linking perception and action (e.g., De Jong et al., 1994; Kornblum et al., 1990). These models hypothesize that, when a stimulus appears, a slow controlled route activates the required response on the basis of task-defined associations (short-term memory links or STM) that connect a stimulus to a particular response, while a fast automatic route activates the response that spatially corresponds to the stimulus location through pre-existing stimulus–response associations, which are independent from the instructions (long-term memory links or LTM). In corresponding trials, this automatically activated response is the same as the one

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indicated by the relevant stimulus feature; therefore, no competition between response codes arises. In noncorresponding trials, on the contrary, the automatically activated response and the response activated on the basis of the relevant stimulus feature are different and a conflict arises which causes a slowing of response time and an increased number of errors.

Several studies have shown that the magnitude of the Simon effect depends on correspondence sequence with the effect being larger after a corresponding trial and smaller (or absent) after a noncorresponding trial (e.g., Hommel et al., 2004; Iani et al., 2009; Iani et al., 2014; Salzer et al., 2013; Soetens et al., 2010; Stürmer et al., 2002). According to some researchers, these effects (from now on *sequential effects*) indicate that the activation through LTM links, considered to be automatic, could be instead influenced by top-down control processes (Mordkoff, 1998; Ridderinkhof, 2002; Stoffels, 1996; Stürmer et al., 2002). For instance, Botvinick et al. (2001) have explained these trial-by-trial adaptations as due to an increase in cognitive control that is driven by the detection of a conflict in the current trial in order to avoid conflict in the following trial (aka, 'conflict monitoring theory'). In other words, the conflict experienced in a trial triggers a series of adjustments aimed at preventing the recurrence of the conflict in the subsequent trial (see Mansouri et al., 2009, for a review). Interestingly, by analyzing PD as a function of correspondence sequence, van Steenbergen and Band (2013) found that the measure mirrored the conflict-adaptation pattern observed in reaction times (RTs). Based on the specific pattern of results obtained, they suggested that pupil diameter might be used as an indirect marker of conflict monitoring.

To note, the Simon effect may also be reduced or even reversed after practicing on a spatial compatibility task with an incompatible S-R mapping (e.g., responding to the left stimulus with the right key and vice versa; e.g., Proctor and Lu, 1999; Tagliabue et al., 2000; Rubichi et al., 2005; Iani et al., 2009; Lugli et al., 2013). To explain how previous practice with a spatially incompatible task changes the cognitive structure to produce a reverse Simon effect, Tagliabue et al. (2000) introduced the notion of "long-lasting short-term links". According to their hypothesis, the STM links between a stimulus location and the incompatible response, set up to perform the spatial incompatibility task, remain active and influence performance in the subsequent Simon task, hence contrasting the overlearned LTM links. According to this view, practice is not supposed to affect the long-term associations, which are considered as unmodifiable.

Both practice and sequential effects can be taken as evidence of an adaptation to specific experiences favoring a specific S–R link, irrespective of task goals and may be interpreted as two forms of cognitive control. However, it is still debated whether the two modulations reflect a unitary mechanism or rather two different mechanisms. For instance, Iani et al. (2009) proposed that practice and sequential effects are independent and additive: practice-induced modulations can be attributed to new S–R links created in the framework of the conditional route, whereas sequential modulations reflect influences on the unconditioned route. More precisely, during the spatially incompatible practice participants learn to associate the spatial information of the stimulus to the response location (right stimulus–left response) and transfer this spatial STM association to the Simon task (red stimulus on the right–left response) (e.g., Lugli et al., 2013). However, this practice does not prevent the system from responding in a flexible way to trial-by trial changes. In line with this idea, Iani et al. (2009) found no interaction between the type of practice (either compatible or incompatible) and sequential modulations when the amount of practice was controlled for (see Exp. 2).

Differently from Iani et al. (2009), Soetens et al. (2010) proposed that sequential modulations interact with practice effects. According to their reasoning, which memory link is activated on each trial depends on the nature of the preceding trial. A preceding corresponding trial activates or primes the corresponding LTM link, leading to the emergence of a Simon effect in the following trial. Differently, a noncorresponding trial primes the task-relevant STM link, leading to the absence of a Simon effect in the following trial. The incompatible practice influences this priming mechanism since it brings to the creation of a new contralateral LTM link that is primed after a noncorresponding trial, leading to a reversal of the Simon effect. This reasoning is mostly based on the observation that, in both in their studies and in the study by Iani et al. (2009), the reversal of the Simon effect following a noncorresponding trial was numerically larger after an incompatible practice than after a compatible practice or in the absence of prior practice. According to such an account, sequential modulations before practice and after practice should differ since in the first case after a noncorresponding trial there is no activation of LTM links (and hence no activation of the unconditional route).

As stated above, the pupillary response has been shown to reflect sequential modulations (van Steenbergen and Band, 2013). Given this sensitivity, it could be used to assess whether prior practice of an incompatible S-R association affects how the cognitive control system works. To this aim, in the present study we required healthy participants to perform a Simon task before (session 1) and after (session 2) practicing a spatial compatibility task with an incompatible S-R mapping. Both RTs and PDs were recorded during the two sessions of the Simon task (sessions 1 and 2).

In line with previous studies, we expected to find larger PDs in noncorresponding trials as compared to corresponding trials and to observe a conflict-related modulation of PD based on correspondence sequence, when the Simon task was performed before practice (session 1). Since an incompatible practice has been shown to reduce or even eliminate the Simon effect, we expected PD to show either no difference between corresponding or noncorresponding trial or a decrease in noncorresponding trials as compared to corresponding trials following the incompatible practice (session 2). If, as suggested by Iani et al. (2009) based on behavioral data, prior practice and correspondence sequence selectively modulate conditional and unconditional processing and do not interact, modulations of PD based on correspondence sequence should be evident even after practice and should not differ between the two sessions. The observation that sequential effects are affected by prior practice could be taken as an indication that the two modulations are not independent. It is also possible that prior practice does not influence PD. This would be an even stronger indication that two independent mechanisms are responsible for sequential and practice effects.

2. Material and methods

2.1. Participants

Twenty-eight right-handed undergraduate students of the University of Oslo (Norway) volunteered to participate in the experiment (mean age: 25.5 years; 16 female and 12 male). All reported normal or corrected-to- normal vision and were naïve as to the purpose of the experiment. All of them performed the Simon task before (session 1) and after (session 2) performing a spatial compatibility task with an incompatible S–R mapping.

The study was conducted in accordance with the ethical standards laid down in Declaration of Helsinki. Written consent was obtained from all participants and they were debriefed about the aim of the study at the end of the experiment.

2.2. Apparatus and stimuli

Participants sat in front of a LCD monitor at a viewing distance of approximately 70 cm. Room illumination was measured using a digital luxmeter and kept constant at 170 lx throughout the whole experiment. Stimulus presentation and response collection were controlled by the Experiment Center software system by SMI (SensoMotoric Instruments, Teltow, Germany). Stimuli were white, red, or blue solid circles