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DOI
10.1016/j.concog.2015.09.005
Publication date
2015
Document Version
Final published version
Published in
Consciousness and Cognition

Consciousness and Cognition 37 (2015) 148–159

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Suppressing the truth as a mechanism of deception: Delta plots reveal the role of response inhibition in lying ☆

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ARTICLE INFO

Article history:
Received 16 October 2014
Revised 26 August 2015
Accepted 9 September 2015
Available online 19 September 2015

Keywords:
Deception
Delta plots
Response inhibition
Reaction time

ABSTRACT

Lying takes more time than telling the truth. Because lying involves withholding the truth, this "lie effect" has been related to response inhibition. We investigated the response inhibition hypothesis of lying using the delta-plot method: A leveling-off of the standard increase of the lie effect with slower reaction times would be indicative of successful response inhibition. Participants performed a reaction-time task that required them to alternate between lying and truth telling in response to autobiographical questions. In two experiments, we found that the delta plot of the lie effect leveled off with longer response latencies, but only in a group of participants who had better inhibitory skills as indexed by relatively small lie effects. This finding supports the role of response inhibition in lying. We elaborate on repercussions for cognitive models of deception and the data analysis of reaction-time based lie tests.

1. Introduction

Any fool can tell the truth, but it requires a man of some sense to know how to lie well.

This quote of the British writer Samuel Butler suggests that lying is a cognitively demanding task. Indeed, a liar may be mentally challenged to keep his story straight, to refrain the truth from slipping out, to keep the truth active while fabricating the lie, and to monitor his own behavior and that of the listener (Vrij, Granhag, & Porter, 2010). In recent years, deception research has dealt in large part with finding empirical evidence for the idea that lying is cognitively more demanding than truth telling (Abe, 2011; Walczyk, Igou, Dixon, & Tcholakian, 2013). In line with the cognitive view of deception, studies have repeatedly shown that response latencies are longer when people lie than when they tell the truth (see Verschuere & De Houwer, 2011, for a review). Further, lying is accompanied by higher activity levels in the prefrontal cortex, a region that

☆ Evelyne Debey was supported by Ghent University Grant BOF01/D01010. Jan De Houwer was supported by Ghent University Grants BOF/GOA2006/001 and BOF09/01M00209. Maarten De Schryver was funded by Ghent University Grant BOF/GOA2006/001.
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http://dx.doi.org/10.1016/j.concog.2015.09.005
1053-8100/

is linked to cognitive control and executive functioning (see Abe, 2011, for a review). While the idea that lying is cognitively more demanding than truth telling has received considerable empirical support in recent years (Vrij & Granhag, 2012), an important question remains which executive functions are engaged in deception.

From the definition that lying involves withholding the truth, several cognitive models of deception have derived that response inhibition – the executive function that allows one to intentionally inhibit a dominant, automatic or prepotent response (Miyake et al., 2000) – may be at the heart of deception (Spence et al., 2004; Vendemia, Schillaci, Buzan, Green, & Meek, 2009; Walczyk, Harris, Duck, & Mulay, 2014). Various lines of research support the notion that the truth is the more dominant response that is activated first during lying, thereby causing response conflict (e.g., Duran, Dale, & McNamara, 2010; Hadar, Makris, & Yarrow, 2012; Johnson, Barnhardt, & Zhu, 2004; Seymour & Schumacher, 2009). Evidence that this response conflict is solved by active inhibition of the truth comes mainly from brain imaging studies that show that lying is accompanied by activity in the inferior frontal gyrus (IFG; Abe, 2011; Vartanian et al., 2013). The IFG is a region most strongly and continuously activated during performance in typical response inhibition tasks (e.g., Aron, Robbins, & Poldrack, 2004; Sebastian et al., 2013), and its importance for efficient inhibition in such tasks has been revealed in studies showing that a disruption of the IFG resulted in impaired task performance (e.g., Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Obeso, Robles, Marrón, & Redolar-Ripoll, 2013). A drawback of brain imaging studies, however, is that they do not allow to draw conclusions about the functional necessity of the activated regions. In that regard, some studies have cast doubt on the hypothesis that the IFG activity during deception reflects the crucial process of response inhibition (Gamer, Klimecki, Bauermann, Stoeter, & Vossel, 2012; Verschuere, Schuhmann, & Sack, 2012). In the study of Verschuere and colleagues, for example, a temporarily disruption of the right IFG induced by continuous theta-burst stimulation (cTBS), a non-invasive brain stimulation technique, did not hamper lying performance in a reaction-time (RT) based lie test.

The objective of the current study was to investigate the role of response inhibition in the act of lying using another methodology. We introduce to the study of deception an analytic technique that has been proven useful to demonstrate and unravel response inhibition in other conflict tasks: delta-plot analysis (see Proctor, Miles, & Baroni, 2011; van den Wildenberg et al., 2010, for reviews). Delta plots have been used to quantify the efficiency of selective inhibition in conflict tasks (Ridderinkhof, 2002a). Delta plots display the RT difference between two experimental conditions (i.e., RT effects) as a function of response time. Conforming to a statistical regularity, RT effects typically become larger as responses slow down, such that the slopes connecting the effect values are positive-going (Wagenmakers, Grasman, & Molenaar, 2005). However, response conflict tasks yield a different delta-plot pattern. In the standard Simon task, for example, participants have to make left or right button presses depending on the color of the stimuli (e.g., press left for red, press right for green). Although the spatial location of the stimuli is task-irrelevant, the Simon effect refers to the finding that responses are slower when the spatial location is incompatible with the required response (e.g., when a red stimulus is presented on the right) than when it is compatible (e.g., when a red stimulus is presented on the left). Plotting this Simon effect ($RT_{incompatible} - RT_{compatible}$) as a function of response time shows a delta-plot slope that levels off for slower responses (e.g., Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; Ridderinkhof, 2002a). Such a leveling-off has also been found when plotting the interference effect in the Eriksen flanker task (e.g., Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2005; Wylie et al., 2010).

Fading conflict effects toward the slow end of the delta plot have been recognized as an important deviation from lawful statistical patterns, underlining the need for a robust theoretical account that predicts such patterns (Pratte, Rouder, Morey, & Feng, 2010; Proctor et al., 2011; Schwarz & Miller, 2012). The activation-suppression hypothesis (Ridderinkhof, 2002a) explains these findings by assuming that interference effects reflect the time to overcome response conflict by inhibiting the dominant task-irrelevant response. As the inhibition mechanism would gradually build up, it would be most effective for slower responses, leading to an attenuation of the interference effect with increasing RTs. Thus, successful response inhibition becomes apparent from a leveling-off of the standard positive delta-plot slope. Proof of principle that delta plots of interference effects vary as a function of inhibition comes from research that demonstrated that delta plots are sensitive to individual differences in inhibitory control. Individuals with good inhibitory control show less positive-going delta-plot slopes than individuals with poor inhibitory control (Ridderinkhof, 2002a). Less negative slopes have also been found in clinical populations that are impaired in their suppression ability, such as individuals diagnosed with ADHD (Ridderinkhof et al., 2005) or Parkinson disease (Wylie et al., 2010). Finally, brain imaging research has confirmed the link between delta plots and inhibitory control by showing that the declining delta-plot slope is associated with activation in the response inhibition region of the IFG (Forstmann, van den Wildenberg, & Ridderinkhof, 2008; Forstmann et al., 2008). Using continuous transcranial magnetic stimulation (cTMS) to instill a virtual lesion in the IFG resulted in preventing the delta-plot slope from declining (van Campen, Kunert, van den Wildenberg, & Ridderinkhof, submitted for publication).

Our study follows the usage of delta plots in the study of individual differences. Based on the assumption that the RT lie effect ($RT_{lie} - RT_{truth}$) reflects the time and effort that is needed to inhibit the truth, we argued that relatively small lie effects are indicative of good inhibitory control, whereas larger lie effects reflect poor inhibitory ability. Consequently, we expected that the delta plot of the lie effect would be less positive-going in participants with relatively smaller lie effects, as their response inhibition mechanism would be able to more efficiently suppress the dominant truth response.

We note here that according to the activation-suppression hypothesis, the gradual development of inhibition should also affect accuracy. Fast responses should be most vulnerable for automatic response capture by dominant action impulses, resulting in a high proportion of fast errors on incompatible trials (Ridderinkhof, 2002a). We investigated response capture in the Sheffield lie test using conditional accuracy functions (Gratton, Coles, & Donchin, 1992). However, because response capture was not the focus of the current study, the analyses are added as Supplementary material.

2. Experiment 1

2.1. Method

2.1.1. Participants

The experiment was carried out with a group of 54 undergraduate students of Ghent University (15 men; M_{age} = 19.54 years, *SD* = 3.04). In return for their participation, they received course credits. The study was approved by the Ethical Committee of Ghent University.

2.1.2. Apparatus

Nine participants performed the Sheffield lie test (cf. infra) on a ASUS A2500H Pentium IV laptop (2.8 GHz Pentium IV processor; 60 Hz 15-in. color monitor). The remaining participants executed the task on a Dell Pentium IV personal computer with an Intel Pentium IV (3 GHz) processor connected to a 60 Hz 17-in. color monitor. The Sheffield lie test was programmed and presented using Inquisit Millisecond Software (Inquisit 1.33, 2002), which allowed to record RTs with millisecond accuracy. Participants sat approximately 50 cm from the screen.

2.1.3. Procedure

The experiment was run in a dimly lit room. Participants were tested in pairs. After giving informed consent, participants performed the Sheffield lie test which took about 20 min. After completing the task, participants were debriefed.

2.1.4. The Sheffield lie test

The Sheffield lie test is an RT-based lie test, in which participants give a speeded manual response to simple yes/no questions that are presented on the screen (Spence et al., 2001). The response labels "YES" and "NO" also appear on the screen according to the response mapping, and their color instructs when to lie or tell the truth. A consistent finding is the presence of a lie effect (i.e., lie minus truth) in errors and RTs (Debey, Verschuere, & Crombez, 2012; Van Bockstaele et al., 2012; Verschuere, Spruyt, Meijer, & Otgaar, 2011).

In the current experiment, twenty neutral yes/no questions that were related to the person or his/her context served as stimuli. Half of the questions required a truthful "yes" response (e.g., "Are you a student?"), whereas the other half required a truthful "no" response (e.g., "Are you having a bath?").[1] Questions were presented in white (Arial, 32 pt., bold) in the middle of a black screen. The response labels "YES" and "NO" were presented at the bottom of the screen (Arial, 32 pt., bold) according to the response mapping. The color of the response labels served as a cue which task to perform: One color (e.g., blue) instructed to lie, whereas the other color (e.g., yellow) indicated to tell the truth. Half of the trials were truth trials; the other half were lie trials. Both the response mapping and the color rule were counterbalanced across participants. The instructions required participants to answer as quickly and accurately as possible pressing the left ("4") or right button ("6") on the numeric key pad of an AZERTY keyboard. The response deadline was 5 s. If no response was given within the response deadline, the next question was automatically presented. The response-stimulus interval (RSI) varied and was either 200 or 2000 ms.[2] After a practice phase of 12 trials, participants performed a test phase consisting of 640 trials, in which every question was repeated 32 times according to the Deception (Truth vs. Lie) × RSI (Short vs. Long) design.

2.2. Data analysis

Trials with anticipatory responses faster than 300 ms (0.07%) and trials with no response within the response deadline of 5 s (0.64%) were eliminated from the analyses. For the reaction time analysis, we discarded trials on which an error occurred (5.66%), and trials with outlying RTs (1.45%). Outliers were removed using a recursive procedure adopted from McCormick (1997; cf. Ridderinkhof & Wijnen, 2011)). For each participant, the fastest and slowest RT of each condition (RSI × Deception) were temporarily removed, and the mean and standard deviation (*SD*) of the remaining data were calculated. If either of the two removed RTs fell outside an interval bounded by 3.5 *SD*s from the mean, it was removed permanently. If the data points

[1] The question "Are you sitting in front of a computer screen?" was removed from the data of the first 9 participants (0.83% data loss), because they performed the task on a laptop, and some participants afterwards reported to have doubted whether a laptop screen also accounted for a computer screen. The question "Are you speaking Serbian?", which was expected to be answered by a truthful "no" response, was discarded from one participant's data because he did speak Serbian (0.09% data loss).

[2] A delta-plot analysis including the factor RSI did not reveal any significant RSI effects. We therefore report analyses across levels of RSI. We note that RSI did explain variance when it was included in the overall mean RT analysis. A significant main effect of RSI, $F(1, 52) = 257.87$, $p < .001$, $f = 2.21$, was subsumed under a Deception by RSI interaction, $F(1, 52) = 5.69$, $p = .02$, $f = 0.33$. This effect demonstrated that the RT lie effect was larger on long RSI trials than on short RSI trials. However, a significant three-way interaction between Deception, RSI and Group, $F(1, 52) = 7.10$, $p = .01$, $f = 0.37$, revealed that this Deception by RSI interaction was significant in the Large lie effect group (Short RSI: *M* = 283 ms, *SD* = 101; Long RSI: *M* = 351 ms, *SD* = 132), but absent in the Small lie effect group (Short RSI: *M* = 83 ms, *SD* = 78; Long RSI: *M* = 79 ms, *SD* = 95). These results replicate and broaden the findings of Debey et al. (2012). In this study, we found evidence for the idea that lying requires executive control by demonstrating that the lie effect is sensitive to an RSI manipulation. Whereas a short RSI has shown to promote attentional focus on task goals, a longer RSI encourages goal neglect, which is especially detrimental in tasks that require executive control as the task goal differs from dominant response tendencies (De Jong, Berendsen, & Cools, 1999; Duncan, 1995). In support for our executive control hypothesis, we found larger lie effects on long RSI trials than on short RSI trials. Assuming that the lie effect reflects particularly the inhibitory facet of executive control, the current experiment extends these findings by showing that only individuals with relatively poor inhibitory control are sensitive to the goal neglect manipulation.

fell within the interval, they were returned to the data set. This procedure continued until no more data points were discarded permanently.

A median split method was used to classify participants into a group with relatively small RT lie effects ($n = 27$) and a group with relatively large RT lie effects ($n = 27$).[3] The median RT lie effect was 165 ms. First, we compared the overall performance between the groups by conducting repeated measures ANOVAs on mean accuracy rates and RTs, with Deception (Truth vs. Lie) as within-subjects variable and Group (Small vs. Large lie effect) as between-subjects variable. Next, RT distributional analyses were performed. Delta plots were obtained by rank-ordering RTs for each condition (Truth vs. Lie) and partitioning them into four equal size quartiles. The RT lie effect was computed for each quartile, and then plotted as a function of the mean RT of the quartile. Finally, the slopes of the segments connecting the RT lie effect values of consecutive quartiles (q1–2, q2–3, and q3–4) were calculated. To find out whether groups differed in inhibitory proficiency, we submitted the slope values to a repeated measures ANOVA with Segment (q1–2, q2–3, q3–4) as within-subjects variable and Group as between-subjects variable. We calculated Cohen's effect size *f* using the following formula: $f = \sqrt{[\eta_p^2/(1-\eta_p^2)]}$. According to Cohen (1992), values from 0.10, 0.25, and 0.40, represent small, medium, and large effects, respectively.

2.3. Results

2.3.1. Mean accuracy

The analysis of accuracy rates yielded a main effect of Deception, $F(1, 52) = 20.92$, $p < .001$, $f = 0.64$, indicative of an error lie effect with less accurate responses on lie trials ($M = 93.41\%$, $SD = 3.35$) than on truth trials ($M = 95.06\%$, $SD = 2.78$). The main effect of Group was marginally significant and showed that the Large lie effect group was slightly more accurate ($M = 94.92\%$, $SD = 2.45$) than the Small lie effect group ($M = 93.56\%$, $SD = 2.97$), $F(1, 52) = 3.36$, $p = .07$, $f = 0.25$. The Deception by Group interaction did not reach significance, $F < 1$.

2.3.2. Mean RT

The lack of a main effect of Group denoted that the groups did not differ in overall RT, $F(1, 52) = 1.34$, $p = .25$. An RT lie effect was present as suggested by the main effect of Deception, $F(1, 52) = 260.57$, $p < .001$, $f = 2.21$. However, this effect was subsumed under a significant Deception by Group interaction, $F(1, 52) = 91.91$, $p < .001$, $f = 1.33$, indicating that, as was to be expected from the way we constructed our groups, the RT lie effect was significantly larger in the Large lie effect group ($M = 317$ ms, $SD = 105$) compared to the Small lie effect group ($M = 81$ ms, $SD = 72$).

2.3.3. Delta plots

Fig. 1 displays the delta plots of the groups; the slope values are displayed in Table 2. Table 1 gives detailed information about the RTs per quartile. A main effect of Segment, $F(2, 104) = 3.80$, $p = .03$, $f = 0.27$, revealed that the slopes varied across quartiles. The main effect of Group, $F(1, 52) = 21.17$, $p < .001$, $f = 0.64$, indicated that the overall delta-plot slope differed between groups. The delta-plot slope was generally positive in the Large lie effect group (significantly different from zero, $t[26] = 7.20$, $p < .001$), whereas it was not significantly different from zero, $t(26) = 1.71$, $p = .10$, in the Small lie effect group. Planned comparisons showed that all slopes differed significantly between groups: q1–2, $F(1, 52) = 19.08$, $p < .001$; q2–3, $F(1, 52) = 20.92$, $p < .001$; q3–4, $F(1, 52) = 6.91$, $p = .01$. In the Small lie effect group, only q1–2 was significantly positive-going, $t(26) = 3.01$, $p < .01$, whereas q2–3, and q3–4 did not significantly differ from zero, $ts \leqslant 1.38$. In the Large lie effect group, all slopes were positive, $ps < .001$. The Segment by Group interaction was not significant, $F(2, 104) = 1.24$, $p = .29$.

2.4. Discussion

This study was successful in replicating a robust RT lie effect in a Sheffield lie test, showing that, compared to truthful answers, deceptive answers were associated with a time penalty. To examine whether the time-consuming process of inhibiting the dominant truth response can account for this RT cost associated with lying, we constructed delta plots in which the RT lie effect obtained was plotted as a function of response speed. We found that delta-plot slopes leveled off with

[3] We acknowledge that the group classification based on median split is arbitrary. Therefore, we additionally divided the sample into three groups based on RT lie effect, and we examined whether we could find the same pattern when we compared the extreme groups (Experiment 1: Small lie effect group [$n = 17$] vs. Large lie effect group [$n = 18$] – Experiment 2: Small lie effect group [$n = 11$] vs. Large lie effect group [$n = 11$]). For both experiments, we again performed the same slope analysis with the factors Segment (q1–2, q2–3, q3–4) and Group (Small vs. Large lie effect group). In Experiment 1, the main effect of Segment was not significant, $F(2, 66) = 1.65$, $p = .20$. In contrast, the main effect of Group, $F(1, 33) = 34.36$, $p < .001$, $f = 1.02$, proved significant. One-sample *t*-tests showed that the slope was overall flat ($M = -.010$, $SD = .091$) in the Small lie effect group, $t < 1$, and positive ($M = .238$, $SD = .150$) in the Large lie effect group, $t(17) = 6.72$, $p < .001$. The Segment by Group interaction was marginally significant, $F(2, 66) = 2.90$, $p = .06$, $f = 0.30$, and revealed that the change of slope values across the quartiles tended to differ between the groups: Whereas in the Small lie effect group the slope values initially decreased and remained flat thereafter (q1–2 = .018; q2–3 = −.057; q3–4 = .008), the slope values in the Large lie effect group became continuously less positive across the quartiles (q1–2 = .267; q2–3 = .257; q3–4 = .189). In Experiment 2, the main effect of Segment, $F(2, 40) = 10.92$, $p < .001$, $f = 0.73$, revealed that across groups, the slope values decreased over quartiles (q1–2 = .195; q2–3 = .076; q3–4 = −.029). Also the main effect of Group, $F(1, 20) = 32.44$, $p < .001$, $f = 1.27$, proved significant. One-sample *t*-tests revealed that the overall slope was negative ($M = -.091$, $SD = .096$) in the Small lie effect group, $t(10) = 3.16$, $p = .01$, and positive ($M = .252$, $SD = .175$) in the Large lie effect group, $t(10) = 4.77$, $p < .01$. The Segment by Group interaction did not reach significance, $F < 1$. In sum, these additional analyses on the extreme groups lead to the same conclusions as the analyses based on the median split method. As such, they show that our results are not dependent upon the specific group classification we use in the main text.

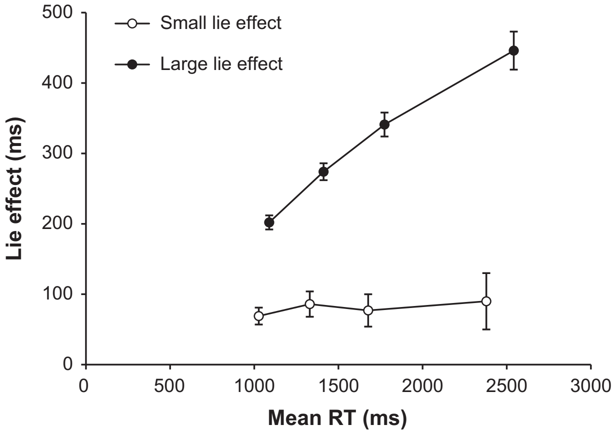

Fig. 1. Delta plots of the Small and Large lie effect group in Experiment 1. The bars represent the standard mean error.

slower RTs in a group of participants with relatively small lie effects, whereas the delta-plot pattern was positive-going in participants with relatively large lie effects. Following the assumptions of the activation-suppression model (Ridderinkhof, 2002a), the finding of a delta plot that levels off points to the involvement of an inhibitory mechanism in the act of lying, that becomes more efficient as it develops over time. The fact that the delta plot leveled off only in the Small lie effect group, shows that this inhibitory mechanism is more efficient in participants whose overall lying performance is better.

Although the change in slope values from q2–3 to q3–4 followed a different direction in the groups (see Table 2), the changes in both groups were small compared to the slopes' relatively large variances, which may explain the lack of a Segment by Group interaction. Within the Small lie effect group, the delta plot did not show a progressive increase as a function of speed, which in itself constitutes a deviation from statistical regularity that demands an explanation (Schwarz & Miller, 2012; Wagenmakers et al., 2005). While an interpretation in terms of inhibition appears consistent with patterns typically reported for conflict tasks, it may be noted that the delta plot observed here does not display the downward slope that is often observed in particular in the Simon task (see van den Wildenberg et al., 2010, for a review). We can think of two explanations. First, the observation that (1) the groups already differed for the slope connecting the fastest RT segments (i.e., q1–2), and (2) decreases in slope values only occurred from q1–2 to q2–3, suggests that the stronger inhibition effect in the Small lie effect group was especially apparent in the fast responses. Such a strong inhibition effect at the beginning of the RT distribution deviates from delta-plot patterns found for typical conflict tasks such as the Simon task, where inhibition effects are particularly apparent in the slower RT segments (van den Wildenberg et al., 2010). This discrepancy may arise from the task characteristics of the Sheffield lie test in the present study. The test requires participants to first read a question before they can execute a response. This slows down overall responding, resulting in a much wider RT distribution compared to classic conflict tasks. Because the RT segments are therefore also relatively wider, inhibition may already be sufficiently strong in the fastest responses. Moreover, the presence of a color cue that instructs to lie – and hence to inhibit the truth – may enforce a quick build-up of inhibition. However, even if the stronger inhibition effect in the Small lie effect group was reflected most strongly in the fastest responses, one may still expect a further development of the inhibition mechanism with increasing RTs, resulting in a further decline of the slope in the slowest segment. The flat slopes in the Small lie effect group may therefore indicate that in the present version of the Sheffield lie test, the need for inhibition, although present (at least in the Small lie effect group), is not as paramount as in the Simon task. We note that in the present experiment, the default settings of the Inquisit experimentation software constrained the number of condition repetitions, such that 75% of all trials entailed a switch from truth to lie responses or vice versa. Deceptive processes (including suppression of truth responses) might be more demanding if deception trials occurred less predictably. Random presentation (resulting in 50% switches) might therefore result in more powerful expressions of deception, and need for inhibition. In order to replicate the novel findings of Experiment 1 in a more pronounced form, we conducted a second experiment with random pre-

Table 1
Means and standard deviations of truth telling and lying per quartile in Experiment 1.

	Small lie effect group				Large lie effect group			
	Q1 *M* (*SD*)	Q2 *M* (*SD*)	Q3 *M* (*SD*)	Q4 *M* (*SD*)	Q1 *M* (*SD*)	Q2 *M* (*SD*)	Q3 *M* (*SD*)	Q4 *M* (*SD*)
Truth telling	993 (164)	1288 (260)	1638 (402)	2334 (670)	989 (140)	1276 (211)	1605 (299)	2321 (529)
Lying	1062 (162)	1373 (254)	1716 (366)	2424 (600)	1191 (174)	1550 (253)	1946 (334)	2767 (487)
Lie effect (lie–truth)	69 (51)	86 (61)	77 (88)	90 (139)	202 (64)	274 (94)	341 (120)	446 (207)

Note. Q = quartile.

Table 2
Means and standard deviations of the slopes in Experiment 1.

	Slope q1–2 *M* (*SD*)	Slope q2–3 *M* (*SD*)	Slope q3–4 *M* (*SD*)	Slope total (q1–4) *M* (*SD*)
Small lie effect group	.070 (.121)	.004 (.147)	.037 (.140)	.037 (.113)
Large lie effect group	.233 (.151)	.198 (.164)	.164 (.207)	.198 (.143)

Note. q1–2 = the slope connecting quartiles 1 and 2.

sentation of lie or truth instructions. Moreover, with the aim to generalize our findings to other types of questions, we now used questions that referred to recently performed activities.

3. Experiment 2

3.1. Method

3.1.1. Participants

Thirty-six undergraduate students (19 men; M_{age} = 18.83 years, SD = 1.16) took part in this experiment, for which they in return received € 5. All procedures complied with relevant laws and institutional guidelines.

3.1.2. Apparatus

The experiment was run on a Dell Optiplex GX520 computer with an Intel Pentium IV (3 GHz) processor that was connected to a 60 Hz 17-in. color monitor. The Sheffield lie test was programmed and presented using Tscope, a C/C++ experiment programming library (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Participants sat approximately 50 cm from the screen.

3.1.3. Procedure

In contrast to Experiment 1 in which the questions in the Sheffield lie test were related to the participant and his/her context, the questions in the current experiment were related to activities that participants had or had not performed in the lab just before taking the Sheffield lie test. Following Debey et al. (2012; Experiment 2), participants performed 10 out of 20 simple activities (e.g., throwing a ball, drawing a triangle). There were four combinations of activities participants were semi-randomly assigned to. To ascertain that participants remembered which activities they had performed, we afterwards displayed all 20 activities one by one on a computer screen, and participants had to indicate whether or not they had performed the activities. After performing the Sheffield lie test which took approximately 20 min, participants were debriefed. Participants were tested individually.

3.1.4. The Sheffield lie test

The Sheffield lie test was similar to that in Experiment 1, except for the following points: (1) The questions concerned the 20 activities that participants had or had not executed in the lab (e.g., "Have you thrown a ball?", "Have you drawn a triangle?"). When a question was related to an activity the participant had performed, it could be truthfully answered by "yes", whereas questions pointing to non-executed activities required a truthful "no" answer. (2) The RSI was kept constant at 300 ms. (3) The ratio of task switch and repetition trials was approximately .50 (in Experiment 1, 75% of all trials were switch trials). (4) The test phase was built of four blocks of 161 trials, separated by self-paced breaks. With the intention to also conduct task switching analyses (not reported in here), every block started with a buffer trial, in which a randomly picked question was presented. Buffer trials were not taken into analyses, leaving 4×160 or 640 trials (each of the twenty questions paired 16 times with the truth cue and 16 times with the lie cue) for the main analyses.

3.2. Data analysis

Trials with responses below 300 ms (0.05%) and trials with no response within the response deadline of 5 s (0.83%) were removed from the data. For reaction time analyses, we removed trials with incorrect responses (5.44%) and trials with RTs that were defined as outlying (1.89%) according to a recursive outlier procedure where the interval boundaries were set at 3.5 *SD*s from the mean of each level of Deception (Truth vs. Lie). Two participants were removed as outliers from further analyses: One participant because her overall RT in the Sheffield lie test (M = 2287 ms) was 2.5 *SD*s removed from the group's mean RT (M = 1482 ms, SD = 292), and another participant because her overall accuracy rate (M = 87.81%) was lower than 2.5 *SD*s from the group's mean accuracy rate (M = 94.47%, SD = 2.41). Based on a median split method, the remaining participants were either assigned to the Small RT lie effect group (n = 17) or the Large RT lie effect group (n = 17). The median RT lie effect was 99 ms. We ran the same analyses as in Experiment 1.

3.3. Results

3.3.1. Mean accuracy

Whereas groups did not differ for overall accuracy, $F < 1$, the main effect of Deception proved significant, $F(1, 32) = 65.69$, $p < .001$, $f = 1.42$. The lack of a Deception by Group interaction, $F < 1$, denoted that the error lie effect did not differ between groups (Small lie effect group: $M = 3.60\%$, $SD = 2.40$; Large lie effect group: $M = 3.21\%$, $SD = 2.49$).

3.3.2. Mean RT

The main effect of Group was not significant, $F(1, 32) = 1.10$, $p = .30$. The main effect of Deception, $F(1, 32) = 50.09$, $p < .001$, $f = 1.25$, was subsumed under a significant Deception by Group interaction, $F(1, 32) = 32.03$, $p < .001$, $f = 1.00$, showing that – as a consequence of how we constructed the groups – the RT lie effect was significantly smaller in the Small lie effect group ($M = 28$ ms, $SD = 62$) than in the Large lie effect group ($M = 253$ ms, $SD = 152$).

3.3.3. Delta plots

Fig. 2 depicts the delta plots of the groups; Table 4 displays the slope values. Mean RT information per quartile is presented in Table 3. A main effect of Segment, $F(2, 64) = 22.64$, $p < .001$, $f = 0.83$, showed that the delta-plot slopes varied across quartiles. Delta-plot slope levels also differed significantly between groups, as evidenced by a significant main effect of Group, $F(1, 32) = 29.95$, $p < .001$, $f = 0.96$. One-sample t-tests showed that the overall slope was significantly positive in the Large lie effect group, $t(16) = 4.73$, $p < .001$, whereas it was negative in the Small lie effect group, $t(16) = 2.76$, $p = .01$. Planned comparisons on each of the slopes separately, revealed that all slopes were significantly different between groups: q1–2, $F(1, 32) = 18.01$, $p < .001$; q2–3, $F(1, 32) = 17.45$, $p < .001$; q3–4, $F(1, 32) = 16.83$, $p < .001$. In the Large lie effect group, q1–2 and q2–3 were significantly, $ps < .01$, and q3–4 marginally, $p = .06$, positive-going. In the Small lie effect group q1–2 followed a positive trend, $p = .09$, whereas q2–3 and q3–4 were significantly negative, $ps \leqslant .02$. A one-sample t-test revealed a marked trend toward a reversed lie effect (−86 ms) in the slowest RT segment, $t(16) = 1.96$, $p = .07$. The Segment by Group interaction did not prove significant, $F < 1$.

3.4. Discussion

As in Experiment 1, participants with larger RT lie effects showed a positive-going delta-plot pattern. In contrast, the delta-plot slopes in the Small lie effect group were not flat as in Experiment 1, but turned negative with slower responses. This result confirms that the lying process comprises an inhibitory component, and shows that this pattern generalizes to different types of truth questions and to different proportions of truth/lie instruction repetitions.

Both groups obtained a pattern of decreasing slope values from segment to segment (see Table 4), which explains why an overall interaction effect remained absent. In contrast to Experiment 1, inhibition thus became stronger with slower RTs, however, this build-up of inhibition was similar among the two groups. Like in Experiment 1, the largest decrease in slopes occurred from q1–2 to q2–3 (i.e., the faster RT segments), which suggests that the build-up of inhibition was the strongest in the fastest responses. Parallel with this strong build-up of inhibition in the fast RT segments, the stronger inhibition effect in the Small lie effect group was again reflected most evidently in the more speeded responses: Just as in Experiment 1, the groups already differed for the slope connecting the fastest RT segments, and with a similar trajectory in slope changes in the groups, this difference remained consistent across slower RT segments.

Notably, the lie effect even reversed in the slowest RT segment. This finding provides yet stronger evidence for the notion that deception involves suppression of the truth, and rules out an alternative account of the leveling-off of the delta plot. Based on the notion of passive decay of the dominant response activation (Hommel, 1994), one might argue that such gradual decay results in a gradual fade-out of conflict effects. Such a decay effect might explain why the delta plots for the RT lie effect level off: If the truth response is activated only transiently and decays rapidly, then slow lie responses might not suffer from interference by the truth response. However, while such a decay account might predict the lie effect to level off, and perhaps even decline toward the slower end of the RT distribution, it cannot explain the reversal of the lie effect in the present experiment. The activation-suppression hypothesis provides a natural account of such reversals, in that the active suppression of the truth response (at the slow end of the RT distribution) results in a relative facilitation of the opposite (deceptive) response.

4. General discussion

A widespread idea in the deception literature is the hypothesis that lying requires response inhibition in order to suppress the dominant truth response (Spence et al., 2004; Walczyk et al., 2014). From such a hypothesis, the longer response times when lying compared to telling the truth (i.e., RT lie effect) may (partly) stem from the time-consuming process of inhibition. We tested this response inhibition hypothesis by applying the delta-plot technique on the RT lie effect obtained in the Sheffield lie test, an RT-based deception test. Delta plots display RT effects as a function of response time and are usually positive-going (i.e., effects become larger with increasing response latencies). However, when inappropriate action impulses interfere with more deliberate correct responses, a gradually developing suppression mechanism can counteract this positive slope by

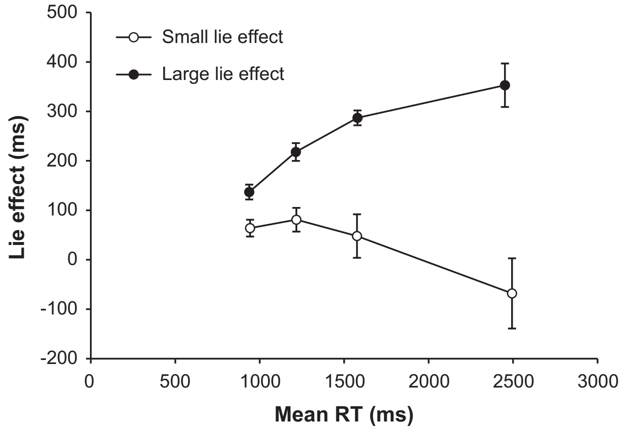

Fig. 2. Delta plots of the Small and Large lie effect group in Experiment 2. The bars represent the standard mean error.

reducing the RT effect with slower reaction times (Ridderinkhof, 2002a). Thus, in conflict tasks such as the Simon task, we typically observe that delta plots tend to slope upward in fast segments, followed by a leveling-off and downward sloping in slower segments (for a review, see van den Wildenberg et al., 2010). We reasoned that if lying involves inhibition, the delta plot of the RT lie effect should level off for slow responses. This leveling-off was expected to be more pronounced in individuals with relatively small lie effects (reflecting effective inhibitory control) compared to individuals with larger lie effects (reflecting poor inhibitory control).

In two experiments, we compared the delta plot of the RT lie effect between a Small and Large lie effect group. Consistent with our hypothesis, we found a clearly positive slope in the Large lie effect group, whereas the delta plot of the Small lie effect group leveled off (Experiment 1) or turned negative and reversed (Experiment 2) at the slow end of the RT distribution. These findings suggest that an inhibition mechanism is involved in the act of lying, that is more efficient in individuals who are generally better at lying. The observation that in both experiments the largest decrease in slope values occurred from q1–2 to q2–3 (i.e., the faster RT segments), and the slope connecting the fastest segments already differed between the groups, suggests that both the build-up of inhibition, as well as the stronger inhibition effect in the Small lie effect group, are most manifest in the more speeded responses. We argued that the design of the Sheffield lie test (e.g., relatively long RTs resulting in wide RT segments, use of task cues) may have enabled the inhibition mechanism to reach robust levels early in the RT distribution. Follow-up research may examine whether the delta plot pattern differs in versions of the Sheffield lie test that allow more speeded responding, for example by blocking truth and lie trials so that no cue processing is necessary on a trial-by-trial basis, and/or by using easier stimuli, such as numbers (odd or even?) or colors (yellow or green?). The fact that the delta plot of the Small lie effect group leveled off in Experiment 1, whereas it was negative-going in Experiment 2 may point to a higher need for inhibition in Experiment 2. First, making the occurrence of lie trials less predictable by balancing the ratio of task switch and repetition trials may have enhanced the need for inhibition in Experiment 2. Second, the use of activity questions may also account for the negative slope in Experiment 2. Because memory for actions is often better than memory for other kinds of information, such as person, object, place or properties (Wagenaar, 1986), and because the activities participants performed were probably still vivid in memory when taking the Sheffield lie test, it may be that the activity questions that were used in Experiment 2 led to a stronger activation of the truth response compared to the person/context questions that were used in Experiment 1. The negative delta plot slope would then reflect the higher need for response inhibition (Ridderinkhof, 2002a). Our study (1) complies with brain imaging studies that show that lying is accompanied by activation in the IFG, a brain region crucially linked to response inhibition (Abe, 2011), and (2) further validates the notion of cognitive models of deception that assigns an important role to response inhibition in lying (Spence et al., 2004; Vendemia et al., 2009; Walczyk et al., 2014).

Table 3
Means and standard deviations of truth telling and lying per quartile in Experiment 2.

	Small lie effect group				Large lie effect group			
	Q1 *M* (*SD*)	Q2 *M* (*SD*)	Q3 *M* (*SD*)	Q4 *M* (*SD*)	Q1 *M* (*SD*)	Q2 *M* (*SD*)	Q3 *M* (*SD*)	Q4 *M* (*SD*)
Truth telling	925 (68)	1199 (145)	1589 (265)	2598 (493)	855 (98)	1073 (154)	1379 (231)	2194 (496)
Lying	993 (101)	1283 (173)	1634 (271)	2513 (530)	991 (126)	1291 (184)	1673 (304)	2557 (620)
Lie effect (lie–truth)	68 (60)	84 (74)	45 (60)	−86 (180)	136 (71)	218 (99)	294 (181)	363 (294)

Note. Q = quartile.

Table 4
Means and standard deviations of the slopes in Experiment 2.

	Slope q1–2 *M* (*SD*)	Slope q2–3 *M* (*SD*)	Slope q3–4 *M* (*SD*)	Slope total (q1–4) *M* (*SD*)
Small lie effect group	.065 (.149)	−.101 (.161)	−.154 (.175)	−.064 (.095)
Large lie effect group	.314 (.191)	.190 (.239)	.071 (.144)	.192 (.168)

Note. q1–2 = the slope connecting quartiles 1 and 2.

There are at least two alternative explanations for our findings. First, an alternative account of fading conflict effects in delta plots might be deduced from the notion of passive decay of response activation (Hommel, 1994). If an initial response is activated only transiently and subject to rapid decay, then such decay might be argued to result in a gradual fade-out of conflict effects. Although this issue has not yet been resolved in a definite manner, most research appears consistent with an active suppression account (Proctor, Yamaguchi, & Dutt, 2012). Moreover, in our study, an explanation of the results in terms of passive decay seems problematic, because mere decay of the truth activation is unlikely to account for the reversal of the lie effect in Experiment 2. Such a reversal effect is predicted directly by the activation-suppression hypothesis, since active suppression of the truth response may, for the slowest responses, become so strong as to result in a relative facilitation of the opposite (deceptive) response.

Second, an anonymous reviewer suggested that our results might be a statistical artifact resulting from the fact that we used the dependent measure to construct the Small and Large lie effect groups. When simulating our observations without assuming an inhibition process,[4] we obtained similar results as we observed empirically, with the slope connecting the slowest RT segments being negative in 24% of the simulations (7% significantly negative). These simulations indicate that a statistical artifact is a plausible option. However, it is possible that the skewness of the RT distribution had a large impact on our results, and consequently on the simulations. Therefore, we constructed delta plots of log-transformed RTs to examine (1) whether similar delta plot patterns could be obtained as with observed RTs, and (2) whether the instances of significantly negative slopes would become negligible in simulations based on these log-transformed data. In both experiments, we found that the log-transformation led to negative-going slopes, even in the Large lie effect groups, with the slope leveling off earlier and more strongly in the Small lie effect groups compared to the Large lie effect groups. Although such patterns differ from those found with observed RTs, they enforce the same conclusion in the sense that the delta plots underline that the Small lie effect groups possess better inhibition skills compared to the Large lie effect groups. The fact that the Large lie effect groups also displayed a negative-going slope strengthens the idea that inhibition is at play in lying. Moreover, simulations of these log-transformed data revealed that the slope connecting the slowest RT segments was now only negative in 9% of the runs (6% significantly negative), which (1) bolsters the notion that the simulations of the observed RTs could be influenced by the skewness of the RT distribution, and (2) makes the statistical artifact explanation less likely.

Follow-up research may examine whether similar delta plot patterns of the RT lie effect can be obtained when groups are formed based on performance on an independent response inhibition task. Because different response inhibition tasks (e.g., Simon task, Go/No-go task, stop-signal task) have found to rely on different subcomponents of response inhibition (interference inhibition, action withholding, action cancellation, respectively; e.g., Sebastian et al., 2013), creating the groups based on a series of different response inhibition tasks will help to specify which response inhibition subcomponent is particularly at play in the act of lying.

Although our studies have good internal validity, we acknowledge that they might lack external validity. One factor that threatened external validity in our studies is that for the same questions, people sometimes lied and sometimes told the truth. This is unlikely to be the case in real life. However, we used such a design to guarantee experimental control and power, because it allowed to compare truthful and deceptive responses that only differed in one factor, that is lying. We further wish to emphasize that the task switching situation our design brought along (i.e., people continuously switched between lying and truth telling) cannot be held responsible for the conflict and the subsequent need for inhibition that would be reflected in the RT lie effect, at least not in Experiment 2 where the repetition/switch ratio was balanced. This conclusion is supported by other studies in our lab which showed that in a balanced design, task switching processes do not contribute to the RT lie effect (Debey, Liefooghe, De Houwer, & Verschuere, 2015).

The delta-plot technique may have the capacity to clarify some unresolved issues in the literature on deception. A first issue relates to the Concealed Information Test (CIT; Lykken, 1959). A classic CIT consists of several multiple-choice questions asking for crime-related information. Each question contains the correct (probe) item and several alternative (irrelevant) items (e.g., "Was the victim killed with a ... (i) knife, (ii) gun, (iii) bat, (iv) rope, (v) candlestick?"). Typically, individuals with crime knowledge exhibit stronger physiological reactions and respond slower to probes than to irrelevant items (see Ben-Shakhar, 2012; Matsuda, Nittono, & Allen, 2012, for overviews). A large body of evidence supports the idea that this probe-vs.-irrelevant effect is due to recognition memory: Probes would only be recognized by culprits as correct

[4] Following the procedure proposed by the reviewer, we simulated response time data for lie and truth trials by randomly sampling from the skewed beta distribution (alpha = 3, beta = 15). For lie trials, values were multiplied by 10,000 and an intercept of 300 was added. For truth trials, values were multiplied by 9800 and an intercept of 250 was added. Then, the outlier procedure as described in our manuscript was applied. As such, data for 50 participants were created. We then classified participants according to the overall lie effect based on the median split. For each participant belonging to the small lie effect group, the slope q3–4 was calculated. We then estimated the mean slope and we performed a *t*-test. This procedure was repeated a 1000 times.

and elicit a stronger orienting reflex than the alternatives (Lykken, 1974). Recently, some studies have suggested that also response inhibition may contribute to the effect (Gamer, Bauermann, Stoeter, & Vossel, 2007; Verschuere, Crombez, Koster, Van Bockstaele, & De Clercq, 2007). Gamer et al. (2007), for example, linked the IFG activity in the CIT to response inhibition. However, this finding was challenged by a more recent study of the authors, in which they argued that the IFG activity may reflect retrieval or relevance detection, instead of response inhibition (Gamer et al., 2012). Applying the delta-plot technique to the RT probe-vs.-irrelevant effect may help to clear out to what extent response inhibition plays a role in the CIT.

A second unresolved issue relates to the proportion truth effect. Previous research has shown that manipulating the proportion of lie and truth trials affects the lie effect, in the sense that a higher frequency of truth trials enlarges the lie effect and a higher frequency of lie trials reduces the lie effect (Van Bockstaele et al., 2012; Verschuere et al., 2011). The question remains which mechanism underlies these changes in the lie effect. Next to explanations relating to task switch costs or an oddball-effect (see Van Bockstaele et al., 2012, for a discussion), a third explanation has been put forward that points to a change in lying efficiency. A higher proportion of truth trials would promote neglect of the task goal to lie, whereas a higher proportion of lie trials would enhance goal maintenance (Duncan, 1995; Kane & Engle, 2003). Given that the task goal of lying entails inhibiting the truth, one could then argue that a high proportion of lie trials would encourage stronger engagement of selective suppression compared to a context containing a higher number of truth trials (see Ridderinkhof, 2002b, for a similar reasoning in the Simon task). Using the delta-plot technique, this goal neglect hypothesis can be tested by examining whether the delta-plot slope of the lie effect in a frequent-lie condition levels off more than the slope in a frequent-truth condition.

Our findings may have practical consequences for RT-based deception detection. So far, the outcome of RT-based lie tests has been mainly discussed in terms of the mean RT cost associated with lying. Our study demonstrates that a delta-plot analysis of this cost reveals information that gets lost in the standard analytic approach based upon overall mean RT. Our experiments show that the effect size of RT lie effects does not only differ between groups (Experiment 1: Small lie effect group [$d = 1.11$[5]] vs. Large lie effect group [$d = 3.01$] – Experiment 2: Small lie effect group [$d = 0.45$] vs. Large lie effect group [$d = 1.67$]), but also within groups as a function of response speed (Experiment 1: Small lie effect group [*d*s from 0.65 to 1.39], Large lie effect group [*d*s from 2.15 to 3.13] – Experiment 2: Small lie effect group [*d*s from 0.47 to 1.14], Large lie effect group [*d*s from 1.23 to 2.20]). In a next step, one could use these findings strategically to improve lie detection. We showed that for individuals with an overall large lie effect, the lie effect was consistently most apparent in the slowest responses. Applied lie detection in these individuals is most likely to be successful based upon analyses of the slowest responses. For individuals with an overall small lie effect, the size of the lie effect varied little with response time. Given the negative slope in Experiment 2, however, it seems wise to analyze particularly the fastest responses. Researchers and practitioners who analyze RT-based lie tests may thus profit from focusing on the slowest or fastest responses depending on the overall mean RT cost of the participant. Instead of merely shifting the focus of the analysis to a specific part of the RT distribution, the RT cost associated with lying may even be actively boosted by strategically manipulating the response deadline in lie tests, so that more slow responses are obtained when examining suspects with weak inhibitory control, and more fast responses when testing suspects with good inhibitory control. Rather than relying on the RT cost in a post hoc manner, another possibility may be to predict beforehand to which group a suspect belongs by pre-assessing his/her response inhibition skills using an independent inhibition task (see Noordraven & Verschuere, 2013, for a similar idea of pre-assessment in the Concealed Information Test). By introducing the delta-plot technique to the field of deception, our study ratified the role of response inhibition in lying. As the delta-plot method has the potential to further expand our theoretical understanding of lying, thereby enabling the development of more accurate lie detection techniques, we hope that our study will encourage its application in future deception research.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2015.09.005.

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[5] As a rule of thumb, Cohen (1988) suggested that *d*s of 0.20, 0.50, and 0.80 represent small, medium, and large effect sizes, respectively.

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