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Interpersonal Touch Enhances Cognitive Control: A Neurophysiological Investigation

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Touch is central to mammalian communication, socialization, and wellbeing. Despite this prominence, interpersonal touch is relatively understudied. In this preregistered investigation, we assessed the influence of interpersonal touch on the subjective, neural, and behavioral correlates of cognitive control. Forty-five romantic couples were recruited ($N = 90$; dating >6 months), and one partner performed an inhibitory control task while electroencephalography was recorded to assess neural performance monitoring. Interpersonal touch was provided by the second partner and was manipulated between experimental blocks. A within-subject repeated-measures design was used to maximize statistical power, with our sample size providing 80% power for even small effect sizes (ds > .25). Results indicated that participants were not only happier when receiving touch, but also showed increased neural processing of mistakes. Further exploratory cognitive modeling using indirect effects tests and drift diffusion models of decision making revealed that touch was indirectly associated with both improved inhibitory control and increased rates of evidence accumulation (drift rate) through its influence on neural monitoring. Thus, beyond regulating emotion and stress, interpersonal touch appears to enhance the neurocognitive processes underling flexible goal-directed behavior.

Keywords: interpersonal touch, emotion, cognitive control, ERN, social neuroscience

Interpersonal touch is a form of nonverbal communication central to mammalian development and socialization. Touch is the first of the major senses to emerge during prenatal development, and tactile interaction between adults accurately communicates a broad spectrum of intentions and emotions (Hertenstein, Keltner, App, Bulleit, & Jaskolka, 2006). Communicative touch also possesses phylogenetic primacy: Touch hypothetically predates language in human evolutionary history and is prevalent across many species with shared ancestry (i.e., nonhuman primates; Dunbar, 2010; Hertenstein, Verkamp, Kerestes, & Holmes, 2006). Furthermore, by making social proximity and interaction salient, affectionate (nonthreatening) touch from close others instils encouragement, calmness, trust, and security, promoting beneficial outcomes including cooperation (Kraus, Huang, & Keltner, 2010), reduced stress reactivity (Coan, 2008; Coan, Beckes, Gonzalez, Maresh, Brown, & Hasselmo, 2017; Coan, Schaefer, & Davidson, 2006), and wellbeing (Debrot, Schoebi, Perrez, & Horn, 2013; Jakubiak & Feeney, 2017).

Despite this primacy, touch has nevertheless received relatively little research attention, particularly in contrast to other major senses and forms of communication. Furthermore, the majority of existing research has focused on touch as a source of communication and/or emotion regulation. Less understood, however, are interactions between touch and other processes that might themselves contribute to health and wellbeing, such as flexible goal-pursuit (Adams, Lawrence, Verbruggen, & Chambers, 2017; Berkman, Falk, & Lieberman, 2011; Brandtstädter & Rothermund, 2002). Here, in a preregistered investigation (see preregistration materials online here: https://osf.io/d9ea4), we explore how interpersonal touch affects the behavioral, neural, and phenomenological processes that underlie flexible goal-directed behavior (i.e., cognitive control).

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Cognitive Control

Cognitive control encompasses multiple processes that monitor and adjust attention, cognition, and action to achieve goals (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miyake et al., 2000). Performance monitoring critically triggers flexible cognitive control by detecting events associated with the need for control (e.g., conflicting impulses, mistakes), and hypothetically relies on activity in the anterior midcingulate cortex (aMCC; Botvinick et al., 2001). This monitoring signal is also reflected in the error-related negativity (ERN): A response-locked event-related potential (ERP) that peaks within 100 ms of making an error (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). This signal is putatively heeded by the dorsolateral prefrontal cortex, capable of then exerting top-down control (Kerns et al., 2004).

But why might interpersonal touch influence cognitive control? Tactile stimulation between individuals—and interpersonal support more broadly—is closely linked to social and affective outcomes (Coan, 2008; Jakubiak & Feeney, 2017; Uchino, Cacioppo, & Kiecolt-Glaser, 1996). Yet, prevalent accounts of cognitive control make little reference to social or affective processes (Botvinick et al., 2001), with affect often considered antithetical to self-regulation in many frameworks (Heatherton & Wagner, 2011; Metcalfe & Mischel, 1999). Consequently, these accounts are agnostic about how touch could potentially interact with cognitive control.

Mounting evidence, however, now indicates that the aMCC responds to negative affect, pain, and cognitive control (Shackman et al., 2011), suggesting that cognitive control might be intrinsically connected with affective processes (Botvinick, 2007; Dreisbach & Fischer, 2015; Inzlicht, Bartholow, & Hirsh, 2015; Koban & Pourtois, 2014; Weinberg, Riesel, & Hajcak, 2012). According to many of these emerging frameworks, the aMCC monitors for negative, affectively charged events (e.g., errors, response conflict, punishment, etc.) and dynamically and flexibly adapts behavior when they are encountered (Inzlicht et al., 2015; Shackman et al., 2011). In this sense, the implementation of cognitive control can be viewed as a form of emotion-regulation motivated by the avoidance of further aversive outcomes (Saunders, Milyavskaya, & Inzlicht, 2015a). Most critical, this framework provides affective and motivational avenues through which social interaction might influence control.

Does Interpersonal Touch Help or Hinder Cognitive Control?

We hypothesized two opposing processes through which interpersonal touch might influence cognitive control. First, the soothing influence of interpersonal touch might diminish cognitive control by reducing the saliency of negative, but nevertheless control-relevant, events, such as errors. Indeed, one seminal neuroimaging study found that canonical subjective and neural responses to painful stimulation were attenuated by interpersonal handholding (Coan et al., 2006). These findings are accounted for by social-baseline theory, which suggests that we come to expect and rely on interpersonal relatedness and social networks that confer multiple survival benefits (e.g., distribution of risk, shared workload; Beckes & Coan, 2011). As such, cues to social proximity can have a calming influence on humans by signaling that self-regulatory efforts can be outsourced to close others (Coan et al., 2006). Most interesting, the effects of interpersonal touch on emotion regulation coincides with reduced activity in neural sites implicated in effortful emotion-regulation (Coan et al., 2006, 2017), further supporting the idea that interpersonal emotion-regulation reduces demands on self-regulatory processes within the individual.

In the context of cognitive control, it is possible that this soothing influence of touch might actually result in diminished cognitive control. Recent affective neuroscience theories of cognitive control suggest that sensitivity to the aversive/punishing quality of control-related signals (e.g., internal error monitoring) acts as a motivational input to cognitive control (Botvinick, 2007; Dreisbach & Fischer, 2015; Inzlicht et al., 2015; Shackman et al., 2011). These theories are supported by a range of recent findings suggesting that various emotion-regulation strategies diminish cognitive control specifically by attenuating neural reactivity to mistakes (Bartholow, Henry, Lust, Saults, & Wood, 2012; Hobson, Saunders, Al-Khindi, & Inzlicht, 2014). Consequently, our first hypothesis was that touch would diminish control by reducing the saliency of negative events (i.e., errors) that are nonetheless useful motivational inputs to adaptive behavioral control. This hypothesis suggests that the calming effects of touch might indirectly have detrimental effects on performance, rather than suggesting that social proximity itself directly impairs cognitive control.

Touch between individuals is also a salient source of happiness, security, and encouragement (Hertenstein et al., 2006; Jakubiak & Feeney, 2017), promoting a second hypothesis that interpersonal touch would have beneficial motivational influences on cognitive control. Consistent with this idea, prior studies have demonstrated that touch increases enjoyment, willingness, and attainment during recreational and academic courses (Legg & Wilson, 2013; Steward & Lupfer, 1987), and it has been suggested that social proximity might boost objective and subjective levels of personal efficacy (Coan & Sbarra, 2015). One further ethnographic study found that professional basketball teams with higher levels of physical interaction (e.g., fist bumps, low fives, hugs) were more cooperative and successful throughout the season (Kraus et al., 2010). In short, these findings suggest that interpersonal touch might have a positive, motivational influence, proposing that touch might enhance cognitive control.

The suggestion that touch does enhance control and positive emotions seems hard to reconcile with suggestions that the aversiveness of errors (cf. Aarts, De Houwer, & Pourtois, 2013; Hajcak & Foti, 2008; Saunders, Milyavskaya, & Inzlicht, 2015b) motivates cognitive control (Inzlicht et al., 2015). Rather than muting aversive experiences, however, positive affect might function to counter defensiveness toward signals that are both informative and threatening (Trope & Neter, 1994). Complimenting a friend or colleague, for example, might make subsequent criticism seem less threatening, allowing the person use this feedback as information without counterproductive dismissiveness or defensiveness. Consequently, supportive states fostered by touch might enhance neural performance monitoring by increasing openness to internally generated negative signals, such as error monitoring. Such a finding would be consistent with recent studies linking enhanced neural error monitoring with emotional acceptance (Legault, Al-

Khindi, & Inzlicht, 2012; Saunders, Rodrigo, & Inzlicht, 2016; Teper & Inzlicht, 2013).

The Current Study

We designed an EEG experiment to determine if interpersonal touch helps or hinders cognitive control. To this end, romantic partners were recruited to participate in the study. Romantic partners were chosen to maximize the power of our touch manipulation—we reasoned that the affective benefits of touch would be higher/more consistent for romantic couples than friends or strangers (cf. Coan et al., 2006). One individual performed an inhibitory control task with an interpersonal touch manipulation (handholding vs. not handholding) provided by their partner, within-subjects. A within-subjects manipulation was chosen specifically to increase statistical power with sample sizes that are achievable for neuroscience investigations. More critically, because of this power advantage, within-subject designs have been demonstrated to be more replicable than between-subjects designs (Open Science Collaboration, 2015). We recorded electroencephalography to assess neural performance monitoring while probing the subjective and affective consequences of touch.

If the emotion-regulatory effects of touch indirectly hinder cognitive control, handholding should diminish neural error monitoring (i.e., reduced ERN amplitude), negative emotions, and inhibitory control. Conversely, if touch helps control, handholding should enhance neural monitoring (i.e., increased ERN amplitude), inhibitory control, and positive affect, as well as reducing self-criticism directed toward personal performance.

Method

Participants

A priori power analyses using G-Power (v 3.1) determined that 32 participants were required to achieve 80% power to detect an effect size of $d = 0.4$ (the estimated average effect size in psychology; Richard, Bond, & Stokes-Zoota, 2003) in a within-subject design. Rather than stopping at 32 participants, we preregistered so that we would collect data from 45 individuals to allow for participant attrition rates that are common in EEG studies of error monitoring (e.g., too few mistakes to compute reliable error-related ERPs, high EEG artifacts). These stopping rules were followed during data collection, and no-interim statistical analyses were conducted before data collection was terminated. Details of preregistered hypotheses, power-analyses, and stopping rules were posted online prior to data collection (https://osf.io/d9ea4).

Forty-five romantic couples ($N = 90$) were recruited through campus advertisements at the University of Toronto Scarborough. Couples were only eligible if they had been dating for at least 6 months ($M = 21.4$ months; range: 6–96 months as reported by the EEG participant). Participation was compensated with $15 CAD per individual ($30 per couple). Only one member of each couple took part in the EEG/performance aspect of the experiment (active partner), while the other participant provided the handholding manipulation (passive partner). Participant assignment was decided before the experimental session with the aim to achieve roughly equal numbers of males and females in each role. Prior studies of interpersonal touch have only investigated the neurophysiological effects of hand holding on emotional responding in female participants (e.g., Coan et al., 2006). However, in the current study we recorded EEG from both male and female participants.

Of the EEG participants ($n = 45$; 20 women; M age = 20.1, range: 18–29), the majority self-identified as heterosexual ($n = 37$), with the remainder identifying as gay or lesbian ($n = 2$), bisexual ($n = 1$), queer ($n = 1$), or uncertain or questioning ($n = 2$). Two further participants did not to disclose their sexuality. The majority of the EEG participants identified their relationship status as "seriously dating one person, but not living together" ($n = 33$), with others selecting "casually dating one person" ($n = 3$), "living with my partner" ($n = 4$), or "engaged" ($n = 2$). Two EEG participants were excluded from the analyses due to excessive high-frequency noise in the EEG signal ($n = 1$) or not completing the experimental task due to technical malfunction ($n = 1$). This meant that our final sample size exceeded our preregistered minimum sample ($n = 32$) by 11 participants. Sensitivity analysis indicated that with our within-subject repeated measures design and final sample size, we could detect even small effect sizes (i.e., $d > .25$) with 80% power (Westfall, 2015).

Procedure

Both partners were seated together inside an electrically shielded room for the duration of the experiment (see Figure 1). The active partner performed the inhibitory control task facing the computer screen, while the passive partner sat to their left. In addition, left-handed participants were assigned to the role of the passive participant so that responses were always made with the dominant hand.

In addition to facing away from the computer monitor, an occluding screen attached to the monitor further ensured that the

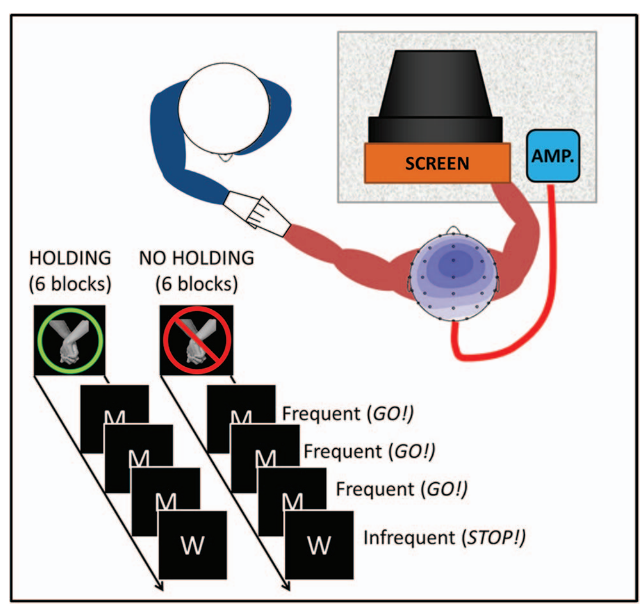

Figure 1. Top right: graphical depiction of the laboratory set-up during the hand-holding manipulation. Bottom left: the inhibitory control paradigm used in the experiment. See the online article for the color version of this figure.

passive partner could not see the task during performance. This set-up was intended to minimize feelings of social evaluative threat during performance (Hajcak, Moser, Yeung, & Simons, 2005). This set-up also ensured that responses to subjective experience questions (detailed later) were confidential during the experiment. Couples were asked not to talk during performance and were specifically instructed not to confer while answering any subjective report questions. Couples were kept in the same physical location so that the handholding manipulation resulted in contrasting levels of interpersonal touch (i.e., touch vs. no touch) while keeping other factors (e.g., presence of partner; unaccounted for nonverbal communication such as eye-contact) constant between conditions.

The active partner performed a speeded inhibitory control task while either holding or not holding their partner's hand. The task was a modified go/no-go task, where the target letter "M" served as the frequent (80% occurrence) and "W" as the infrequent (20% occurrence) stimulus. The asymmetrical ratio of target stimuli ensures a prepotent response tendency in favor of the frequent stimuli, with inhibitory control required to overcome this impulse on infrequent targets. Participants pressed the left arrow key with their right index finger if they saw an "M" target, and the right arrow key with their right middle finger in response to the infrequent "W" targets. Key-presses were made with one hand so that the other hand was free for the touch manipulation.

Trials started with a fixation cross for 200 ms, followed by the brief (200 ms) presentation of a target letter in white font on a black background. The screen then remained blank until response commission (max: 1,000 ms) followed by a white fixation cross (400 ms) before the next trial.

Participants first completed 20 practice trials, before moving on to 840 experimental trials. The experimental trials were divided into 12 blocks of 70 trials, separated by the subjective report questions and a self-paced rest period. Handholding was manipulated in a block-wise manner: six handholding blocks, six no handholding blocks. The passive partner remained present in the same seated position throughout both conditions, and on-screen instructions told participants when to start and stop holding hands. Participants were asked to hold hands with their partner as they normally would, without doing anything that might be distracting (e.g., stroking the palm with their thumb). The order of the handholding manipulation alternated in groups of three blocks (e.g., Blocks 1–3 = handholding, Blocks 4–6 = no-handholding, Blocks 7–9 = handholding; and Blocks 10–12 = no-handholding) with block-order counterbalanced between participants.

Subjective experience questions were presented between blocks. Participants were first instructed to "Please answer the following questions about your feelings during the block of trials you just did, using numbers 1–7," on a scale ranging from 1 (*not at all*) to 7 (*very much*). Three specific questions asked participants to report their affective experience: anxiety ("I felt anxious during the past block?"), frustration ("I felt frustrated during the past block"), and happiness ("I felt happy during the past block"), whereas two further questions probed other aspects of phenomenological experience that tested the effects of handholding on emotional acceptance: self-judgment ("I told myself not to feel bad about my performance") and self-criticism ("I criticized myself during the past block"). Finally, participants reported levels of effort during performance ("I tried hard during the past block") to test for differences in exertion between conditions. The order of question presentation was randomized within participants between blocks.

The passive partner left the room after the inhibitory control task was over so that the active partner could answer a number of self-report scales relating to relationship quality and demographics. Moderation analyses revealed that no handholding effects were moderated by any of these self-report measures, and this self-report data is available on our OSF page. These scales were then completed by the passive partner while the active participant washed their hair after removing the EEG apparatus.

EEG Preprocessing and ERP Analyses

Continuous EEG activity was recorded from 36 Ag/AgCl sintered electrodes embedded in a stretch-lycra cap arranged according to the international 10–20 system. Vertical electro-oculography was monitored using a supra- to suborbital bipolar montage surrounding the right eye. Impedances were monitored (<5 KΩ) during recording and the EEG signal was digitized at 1024 Hz using ASA acquisition hardware (Advanced Neuro Technology, Enschede, the Netherlands). The data were band-pass filtered offline (high-pass: 0.1 Hz; low-pass: 20 Hz) and corrected for eyeblinks using regression-based procedures (Gratton, Coles, & Donchin, 1983). Semiautomatic procedures were used to detect and reject EEG artifacts using Brain Vision Analyzer (v.2.0; Brain Products, GmbH, Gilching, Germany). The criteria applied were a voltage step of more than 25 μV between sample points, a voltage difference of 150 μV within 200-ms intervals, voltages above 85 μV and below −85 μV, and a maximum voltage difference of less than 0.05 μV within 100 ms intervals. Intervals were rejected on an individual channel basis to maximize data retention.

ERPs were created by segmenting the continuous EEG data into 1,400-ms segments that commenced 400 ms before the response. The ERPs were baseline corrected using a 100-ms interval that started −150 ms before the response and averaged separately as a function of accuracy (error vs. correct) and condition (handholding vs. nonhandholding). The ERN and corresponding correct-related negativity were calculated for presentation purposes. However, statistical analyses focused on the difference activity (ΔERN) obtained by subtracting correct trial activity from the error trial activity. The ΔERN, therefore, indicates how much the brain differentiates between error and correct trials.

The ΔERN was defined as the negative maxima 0 to 120 ms at electrode FCz, relative to the most positive potential proceeding the response (−100 to 0 ms). These search windows were selected to reflect the canonical temporal characteristics of the ERN and match the techniques used in our prior publications to quantify the ERN (e.g., Saunders et al., 2015b, 2016). This peak-to-peak analysis is also preferable both because it allows a baseline free operationalization of the ERN and because it is implemented relatively automatically—these factors reduce the influence of so-called "experimenter degrees of freedom" on our ERP analyses.

In addition to the ΔERN, we analyzed the error positivity (Pe) to provide a comprehensive account of error-monitoring processes. The Pe rises after the ERN, is more broadly distributed around centro-parietal electrode sites and is associated with the motivational significance of mistakes and conscious error awareness (Falkenstein et al., 1991; Gehring et al., 1993). As the Pe does not have a clearly defined peak, the amplitude of this component was determined as the mean amplitude at Pz 200 to 400 ms after the response using a collapsed localizer method on the difference waveform (Luck & Gaspelin, 2017).

Primary Statistical Analyses

All primary hypothesis tests were conducted with multilevel modeling (MLM) using the MIXED function in SPSS (v. 22.0). We first tested the effect of interpersonal touch on subjective experience. Each self-report question (anxiety, frustration, happiness, self-judgment, and self-criticism) was analyzed as a function of the handholding manipulation (effect coded: not-holding = −1; holding = 1). These MLMs had a two-level structure. Unstructured variance was used to estimate a random intercept for each participant.

All ERP data was analyzed in an identical manner to the self-report data, with either the amplitude of the ΔERN or ΔPe included as the dependent variable. Participants were still included in the case of partially missing data (n = 1; missing ΔERN amplitude in no handholding condition) due to having too few usable error trials in the EEG data (see also Saunders et al., 2015b). For the behavioral data (mean reaction times [RTs] and choice error rates), MLMs included the additional effects of conflict level (−1 = low-conflict; 1 = high-conflict) with data aggregated at the level of the block. RTs were only considered for trials with correct responses. Thus, the behavioral analyses now had a three-level nested structure due to the inclusion of conflict-level (i.e., conflict-level within condition within participant). Unstructured variance was used to estimate a random intercept for each participant.[1]

For all analyses, effects were determined to be statistically robust if the 95% confidence intervals (CIs) for the given main effect or interaction did not span zero. Semipartial R-^{2} (R^2_β) is reported as an effect size for each model effect (Edwards, Muller, Wolfinger, Qaqish, & Schabenberger, 2008).

Results

Subjective Experience

We first tested the influence of interpersonal touch on subjective experience. Participants reported increased happiness when holding hands with their romantic partner compared to when they did not hold hands (b = −0.89, SE = 0.21), 95% CIs [−1.31, −0.47], R^2_β = .29 (see Figure 2). No other significant effects were found for specific subjective experiences. However, as anxiety and frustration were particularly highly correlated, $r(86) = .713$, $p < .001$, we conducted a further exploratory analysis by averaging these measures to create an aggregate negative affect score. Here, the handholding manipulation was associated with reduced negative affect relative to the no handholding condition (b = 0.29, SE = 0.14), 95% CIs [0.008, 0.57], R^2_β = .09. It is noteworthy, however, that this reduction in negative affect has a considerably smaller effect size when compared to the large increase in happiness associated with handholding.

ERP Results

ΔERN. A one-sample t test confirmed that the ΔERN amplitude (M = −11.50 μV; SE = 0.78), was significantly more negative than zero, $t(84) = -14.66$, $p < .001$. The amplitude of the ΔERN was more negative during the handholding (M = −12.61 μV, SE = 1.13) condition compared to the nonhandholding (M = −10.75 μV, SE = 1.13) condition (b = −0.93, SE = 0.40), 95% CIs [−1.73, −0.13], R^2_β = .12 (see Figure 3). This result indicates that neural performance monitoring processes that unfold within 100 ms of the mistake were enhanced in the interpersonal touch condition, relative to the control condition.

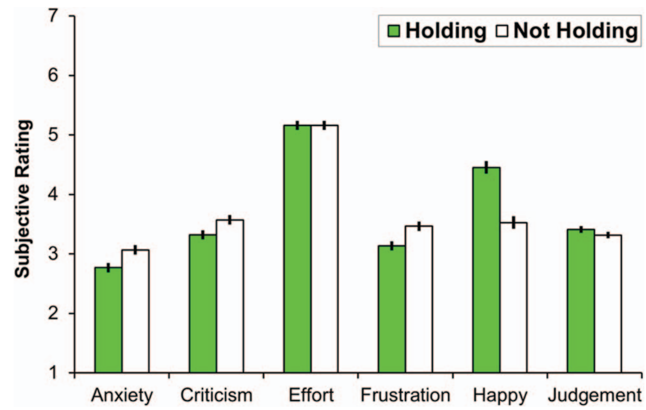

Figure 2. Subjective experience ratings as a function of the handholding manipulation. Error bars represent within-subject standard errors. See the online article for the color version of this figure.

ΔPe. Confirming the classic effect, the ΔPe was significantly more positive than zero, $t(84) = 12.53$, $p < .001$. In contrast to the ΔERN, the ΔPe did not differ between the handholding (M = 9.79 μV, SE = 1.14) and the nonhandholding conditions (M = 10.32 μV, SE = 1.14), (b = −0.27, SE = 0.37), 95% CIs [−1.02, 0.49], R^2_β = .01, see Figure 3, lower panels. Thus, while handholding led to increased neural reactivity to errors within the time-course of the ΔERN (i.e., 0–100 ms), interpersonal touch was not associated with differences in later aspects of error processing that arise 200–400 ms after the response.

Behavioral Data

RT. Participants responded more slowly on high-conflict than low-conflict trials (b = 57.57, SE = 1.27), 95% CIs [55.07, 60.07], R^2_β = .87, confirming that the manipulation of conflict was successful in response times, see Table 1. However, we found no main effect of handholding on RT (b = −0.28, SE = 1.28), 95% CIs [−2.79, 2.23], R^2_β < .001, and no interaction between handholding

[1] We additionally quantified posterror slowing effects and interchannel phase consistency in the theta EEG band between electrode FCz and frontolateral sites (F7 and F8). However, neither measure showed a main effect of trial-type (i.e., error vs. correct) meaning that these variables could not be used to test our hypotheses. We also conducted an exploratory analysis of error-related electromyographic activity over the corrugator muscle of the face (Lindström, Mattsson-Mårn, Golkar, & Olsson, 2013). Although this measure did show a main effect of trial-type, unlike the ERN results, this main effect did not interact with handholding condition. This finding is consistent with our earlier finding that error-related corrugator activity does not covary with the amplitude of the ERN (Elkins-Brown, Saunders, & Inzlicht, 2016). These findings suggest that the functional significance of the error-related corrugator activity requires further elucidation in ongoing research.

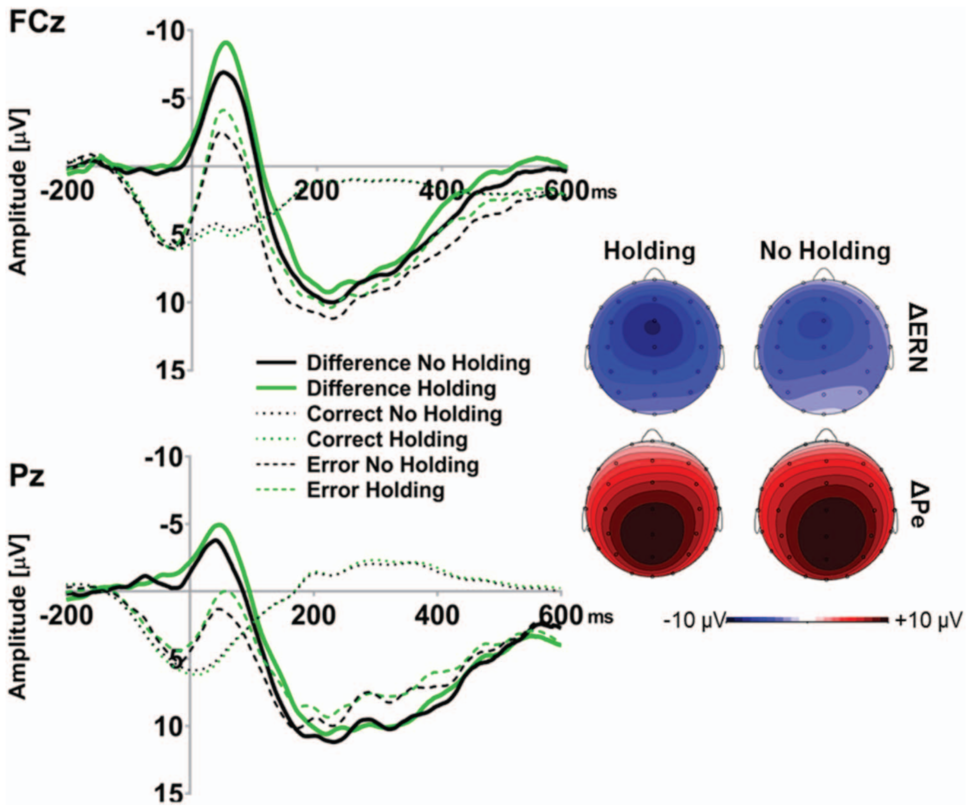

Figure 3. Left panels: Waveforms depicting the effects of interpersonal touch on error-related potentials (ERPs) at electrodes FCz and Pz. Right panels: Spline maps depicting the topographical distribution of the neural error monitoring (ΔERN; 30–80 ms—time period chosen for illustrative purposes) and ΔPe (200–400 ms) across levels of the handholding manipulation. See the online article for the color version of this figure.

and conflict level ($b = -0.23$, $SE = 1.28$), 95% CIs [−2.74, 2.28], $R^2_\beta < .001$.

Choice error rates. Percentage error rates were higher on high-conflict compared to low-conflict trials ($b = 12.35$, $SE = 0.38$), 95% CIs [11.61, 13.09], $R^2_\beta = .70$ (see Table 1). However, as with RTs, there was no significant main effect of the handholding manipulation, ($b = 0.24$, $SE = 0.38$), 95% CIs [−0.50, 0.98], $R^2_\beta < .001$, nor did this interact with conflict-level ($b = 0.27$, $SE = 0.38$), 95% CIs [−0.47, 1.01], $R^2_\beta < .001$. In conjunction with the RT results, these findings suggest that we observed robust performance decrements on conflicting compared to nonconflicting trials, however, these effects were not directly altered by interpersonal touch.

Table 1
Descriptive Statistics for the Behavioral Data

Dependent measure	No holding		Holding	
	M	*SE*	*M*	*SE*
Reaction time (ms)				
Low conflict	352	6.33	352	6.33
High conflict	468	7.21	467	7.90
Error rates (%)				
Low conflict	.82	.11	.76	.14
High conflict	24.99	2.55	26.01	2.13

Exploratory Process Analyses

In addition to the above analyses, we conducted two additional exploratory analyses to further investigate the relationship between cognitive control and interpersonal touch. First, we used indirect effects tests to assess if interpersonal touch indirectly influences behavioral performance through handholding's effects on neural performance monitoring. Second, we used a variant of drift-diffusion modeling (EZ-diffusion model; Wagenmakers, van der Maas, & Grasman, 2007) to extract the latent cognitive processes that underlie observed behavior on our two-alternative forced choice task and test if these processes are also indirectly influenced by the effect of interpersonal touch on neural monitoring. Interestingly, although EZ drift-diffusion modeling is a simplified modeling technique, it was recently found to perform as well as more complex models, as determined by a series of blind analyses (Dutilh et al., 2016). Both of these analyses are exploratory in nature and should be treated with some caution since neither the indirect effects tests nor the EZ-diffusion modeling were included in our preregistration documents.

Does interpersonal touch alter behavior indirectly through its influence on neural error monitoring? Structural equation modeling (SEM) was used to explore the relationships between touch, performance monitoring, and accuracy. Here, we conducted an indirect effects test to determine if the handholding manipulation had a significant indirect effect on cognitive control through its effect on neural performance monitoring (i.e., ΔERN amplitude). Unlike mediation effects where the direct effect of the independent variable on the outcome measure is prerequisite to testing mediation, indirect effects test potential process variables without requiring an initial direct effect (Preacher & Hayes, 2004).

The path analyses were conducted using the lavaan survey package in R statistics software. Difference scores were used to operationalize both the behavioral conflict effect (Δ % errors = error rates on high-conflict trials minus error rates on low-conflict trials) and error monitoring as the intervening variable (i.e., ΔERN). The degrees of freedom in our SEM were 0, suggesting that the model is just identified. This outcome suggests that we can interpret the paths defined in our model but cannot generate reliable fit statistics to compare the model to other possible path architectures.

The model revealed a significant indirect effect, $b = -2.691$, $SE = 1.160$, $Z = -2.320$, $p = .02$ (see Figure 4). Here, handholding was associated with increased ΔERN amplitudes, $b = -2.246$, $SE = 0.943$, $Z = -2.381$, $p = .017$, and this increased neural monitoring predicted reduced error rates on the task at hand, $b = 1.198$, $SE = 0.227$, $Z = 5.284$, $p < .001$. Thus, these analyses suggest that touch indirectly improved behavior through its enhancing effect on neural monitoring. Finally, in addition to this indirect effect, a significant direct path suggested that handholding was associated with poorer control when ΔERN was defined as an intermediary variable in the model, $b = 3.113$, $SE = 1.584$, $Z = 1.966$, $p = .049$. This result was unanticipated, and, as such, should be considered with some caution. However, the emergence of this direct path when the indirect path was accounted for might suggest a suppression effect. Although the source of this suppression is unclear, it is possible that the handholding manipulation was distracting for some participants, resulting in more errors on the inhibitory control task without effecting neural monitoring after accounting for the indirect route through which the ERN was amplified by handholding. No significant indirect effects were observed for the equivalent model using mean RT as the outcome variable.

EZ-diffusion cognitive modeling. The EZ-diffusion model is a simplified version of classic drift-diffusion modeling techniques (e.g., the Ratcliff diffusion model; cf. Ratcliff & McKoon, 2008) that can be used to estimate latent cognitive decision processes

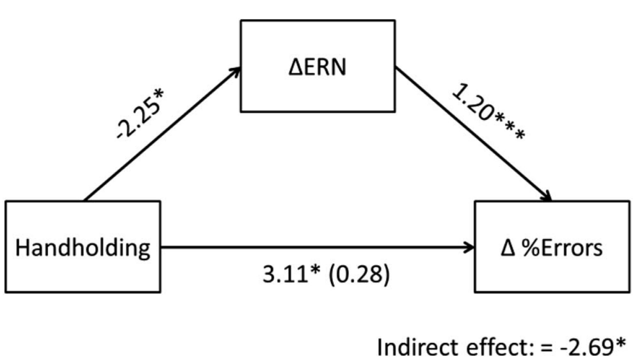

Figure 4. Path analysis of the indirect effects model investigating the effect of handholding on performance (Δ% errors) through neural error monitoring (ΔERN). Unstandardized regression coefficients are presented along paths. * $p < .05$. *** $p < .001$.

from two-alternative forced choice tasks (Wagenmakers et al., 2007). Akin to other forms of drift-diffusion modeling, the EZ-diffusion assumes that a noisy information/evidence accumulation process underlies decisions between defined alternatives (e.g., identifying the letter "M" or the letter "W" in our task), with this decision-making process terminating when evidence for one of the mutually exclusive responses reaches a certain threshold or boundary value (see Figure 5).

One drawback of classic drift-diffusion modeling is that it often requires many trials modeling the entire RT distribution, in addition to considerable computational knowledge to implement and extract parameters reliably (cf., Dutilh et al., 2012; Wagenmakers et al., 2007). The EZ-diffusion model, conversely, allows the three most common drift-diffusion parameters (drift rate, boundary separation, and nondecision time) to be reliably estimated in smaller data sets with considerably lower computational demands. The EZ-diffusion model was fitted to our data using the online JavaScript analysis program (http://www.ejwagenmakers.com/EZ.html). EZ-diffusion parameters were calculated separately and averaged across trial-types (high-conflict, low conflict). The extracted parameters were then compared between the handholding and no-handholding conditions.

Drift rate (v). This parameter reflects the level of evidence-accumulation from the target stimulus. High values of drift rate can be understood as a good signal-to-noise ratio where increased values reflect increased rate of approach to the upper (~correct) decision boundary. In between-conditions comparisons, drift rate can be interpreted as a measure of task difficulty (Wagenmakers et al., 2007). Overall, we found no direct difference in drift rate between the handholding ($M = 1.629$, $SE = 0.049$) and no-handholding ($M = 1.585$, $SE = 0.049$) conditions ($b = 0.022$, $SE = 0.018$), 95% CIs [−0.013, 0.058], $R^2_\beta = .04$, in these exploratory analyses.

Boundary separation (a). This parameter reflects the overall level of evidence required to reach a decision boundary, and, as such, boundary separation primarily reflects response caution and speed–accuracy trade-offs (e.g., sacrificing decision speed for increased accuracy). Boundary separation did not differ between the handholding ($M = 0.053$, $SE = 0.002$) and no-handholding ($M = 0.055$, $SE = 0.002$) conditions ($b < -0.001$, $SE = .001$), 95% CIs [−0.003, 0.001], $R^2_\beta = .03$, suggesting that our manipulation did not make decision thresholds more or less conservative.

Nondecision time (Ter). This parameter reflects time dedicated to mental processes that are common to both choice options, and are not related to the decision making process. As such, RT reflects the summation of both decision and nondecision components. As with the other EZ-diffusion parameters, nondecision time did not differ between the conditions of our experiment (handholding: $M = 0.563$, $SE = 0.009$; no-handholding: 0.564, $SE = 0.009$; ($b = -0.0005$, $SE = 0.002$), 95% CIs [−0.005, 0.004], $R^2_\beta = .009$).

Indirect effects tests. Using the same modeling strategy as with overall choice error rates, we conducted indirect effects tests to explore if the parameters of the EZ-diffusion model and are impacted indirectly through the effect of handholding on neural performance monitoring. Although the indirect effects for the models including nondecision time ($b = 0.005$, $SE = 0.003$, $Z = 1.627$, $p = .104$) and boundary separation ($b < 0.001$, $SE < 0.001$, $Z = 1.656$, $p = .098$) as primary outcome variables were not

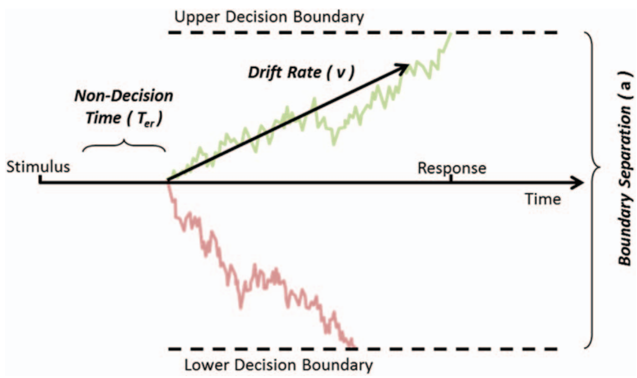

Figure 5. Overview of the EZ-diffusion model. See the online article for the color version of this figure.

significant, we did observe a significant indirect path between handholding condition on drift rate indirectly through the effects of interpersonal touch on the ΔERN ($b = 0.053$, $SE = 0.024$, $Z = 2.226$, $p = .026$), see Figure 6.

These exploratory findings provide preliminary evidence suggesting that the extent to which ERN amplitudes were increased by handholding indirectly predicted an increased rate of evidence accumulation during the inhibitory control task. These findings lend further support to the suggestion that interpersonal touch enhances cognitive control, albeit indirectly through its effects on neural performance monitoring.

Discussion

Despite the established importance of touch for emotional and physical wellbeing (Coan, 2008; Jakubiak & Feeney, 2017), touch remains relatively understudied compared to other major senses and forms of communication. For the first time, we tested the impact of nonthreatening touch between romantic partners on the neural, behavioral, and subjective correlates of cognitive control. Our results suggest that interpersonal touch enhances the intrapersonal neural monitoring processes that detect the need for cognitive control. Furthermore, our exploratory process analyses provided preliminary evidence that this enhanced monitoring also indirectly predicts improved inhibitory cognitive control and rates of evidence accumulation derived from the EZ-diffusion cognitive model. Existing theorizing has indicated that interpersonal touch shows ontogenetic primacy across mammalian species, with existing research indicating the beneficial influences of supportive interpersonal touch for socialization, wellbeing, and emotion-regulation (Coan, 2008; Debrot et al., 2013; Hertenstein et al., 2006). Our results suggest that the positive influence of interpersonal touch might extend beyond these domains by facilitating the neurocognitive processes underlying flexible goal-directed behavior (i.e., cognitive control).

These findings are broadly consistent with the hypothesis that interpersonal touch helps, rather than hinders, cognitive control. Prior work has indicated that supportive touch elevates enjoyment and attainment during effortful individual performance (Legg & Wilson, 2013; Steward & Lupfer, 1987) and boosts cooperation and attainment in competitive sports teams (Kraus et al., 2010). Our findings may provide insight into the potential neural process underlying these prior findings, suggesting that touch might facilitate performance by enhancing the neural monitoring processes that underlie flexible goal-directed behavior. Further consistent with our conclusions, one recent investigation reported that simulated supportive touch (holding a teddy bear) was also associated increased ERN amplitudes (Tjew-A-Sin, Tops, Heslenfeld, & Koole, 2016). Although simulated touch likely cues social proximity less authentically than handholding from a close relationship partner, these conceptually similar studies converge to suggest that touch (both real and simulated) enhances this neural correlate of cognitive control.

Why Might Touch Enhance Neural Monitoring?

Addressing why touch might increase neural monitoring can be informed by considering the effects of touch on subjective experience in the context of cognitive control. Broadly speaking, our results fit within existing frameworks suggesting that interpersonal touch has beneficial effects on emotion regulation (Coan, 2008; Jakubiak & Feeney, 2017). Touch produced large and robust increases in positive affect (i.e., self-reported happiness), while showing more modest reductions on a composite measure of negative affect. As most accounts integrating affect and neural monitoring focus on the negative valence of mistakes (Aarts et al., 2013; Inzlicht et al., 2015; Weinberg et al., 2012), it should be asked how a manipulation that largely increased happiness, and to a smaller extent reduced negative emotions, could sensitize individuals to negative error signals.

According to one account, positive experiences buffer against the threat of negative information, making people more open to signals of personal limitation (Trope & Neter, 1994). As such, touch potentially enhanced neural monitoring for negative, internally generated feedback signals (i.e., the ERN) by reducing natural tendencies to ignore or downplay threats associated with personal shortcomings. Supporting this idea, one recent study reported that a positive mood induction led to enhanced ERN amplitudes during probabilistic learning (Bakic, Jempa, De Raedt, & Pourtois, 2014). However, as touch had no effect on self-criticism or self-judgment, our results do not fully support the idea that handholding increased emotional acceptance. Given the findings of the current experiment, in addition to the mixed effects of

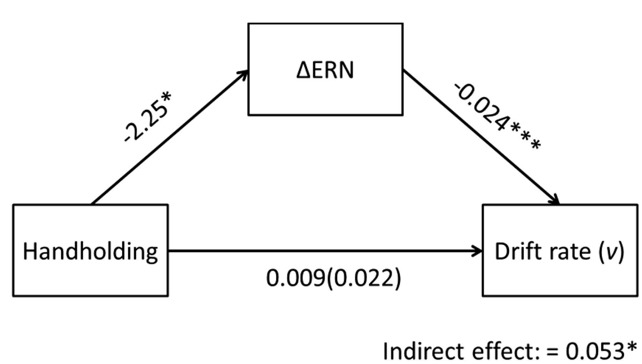

Figure 6. Path analysis of the indirect effects model investigating the effect of handholding drift rate (v) through neural error monitoring (ΔERN). Unstandardized regression coefficients are presented along paths. * $p < .05$. *** $p < .001$.

positive emotion on the ERN in past studies, alternative accounts of our findings should be considered.

One possibility is that partner presence increases evaluative threat during performance, increasing the salience of errors when people feel judged. Indeed, it has been found that interpersonal evaluation leads to increased ERN amplitudes (Hajcak et al., 2005; Masaki, Maruo, Meyer, & Hajcak, 2017), whereas the presence of a close other is sometimes accompanied with increased cardiovascular reactivity during stressful tasks (i.e., mental arithmetic; Allen, Blascovich, & Mendes, 2002). This evaluative threat account seems less plausible in our study, however, because the passive partner could not observe the accuracy of the active partner during performance (confidentiality of responding was ensured by a screen and the physical position of the passive partner, participants were instructed not to converse). Furthermore, active partners experienced more positive affect and less negative affect during handholding without significant increases in self-judgment or self-criticism. Thus, we found little support for the idea that error monitoring was elevated because touch increased a sense of interpersonal evaluation or threat. This finding is consistent with earlier suggestions that interpersonal support reduces stress reactivity in performance contexts that minimize partner evaluation (Kamarck, Manuck, & Jennings, 1990).

A third, and perhaps more likely, possibility is that touch made performance more intrinsically motivating. *Intrinsic motivation* refers to a self-sustaining drive to enact goals that are inherently enjoyable and is improved when contexts support autonomy, security, and social relatedness (Deci & Ryan, 2000). By cueing social proximity and amplifying state happiness, interpersonal touch might have introduced the basic ingredients underlying intrinsic motivation. Thus, rather than affective and social aspects of touch having individual and parallel influences on cognitive control, both enjoyment and social support might have acted in unison to produce the observed enhancement. Supporting this suggestion, Tjew-A-Sin et al. (2016) demonstrated that simulated touch led to particularly large ERNs for individuals high in trait intrinsic motivation. In another study, induced intrinsic motivation enhanced ERN amplitudes (Legault & Inzlicht, 2013). This motivational account is particularly appealing because it can be reconciled with empirical reports that extrinsic incentives (i.e., rewards and punishment) enhance neural monitoring (Hajcak et al., 2005; Saunders et al., 2015b), and with theoretical frameworks in which error monitoring is linked to reward-prediction error (Holroyd & Coles, 2002): When task engagement feels good, is intrinsically rewarding, and is socially supported, worse than expected events (i.e., mistakes) might become particularly salient.

Several prior investigations have noted that the ERN is moderated by motivational variables (see Hajcak, 2012), however, many of these studies have investigated motivational inputs to control through external manipulations that are negatively valenced (e.g., punishment, loss of rewards; Hajcak et al., 2005; Riesel et al., 2012). Although reward omission and punishment are certainly effective at increasing the ERN, these external manipulations (particularly punishment) elevate a range of unwanted negative emotions including feelings of anxiety, frustration, and hopelessness (Saunders et al., 2015b). In contrast, our manipulation of interpersonal touch not only brought about positive emotional states, but also increased neural aspects of cognitive control. Unlike other motivational moderators of error monitoring, social support might enhance these neural processes without undermining the individual's mood or feelings of self-efficacy. It is perhaps only by inducing these more positive, supportive states that interpersonal touch indirectly improved inhibitory control and the rate of evidence accumulation through neural error monitoring.

Future Directions and Limitations

Our findings are generative, and we end by providing ideas for future research questions. Touch can communicate different emotions (Hertenstein et al., 2006), with varied outcomes depending on relationship status. In addition to replicating the results found in the present investigation, future work should explore the influence of different forms of touch across varying classes of relationship. More energizing and platonic forms of touch (fist bumps, high fives), for example, have been related to cooperation (Kraus et al., 2010). Ongoing research could test how different forms of touch facilitate cognitive control in both cooperative and competitive contexts (cf., de Bruijn, de Lange, von Cramon, & Ullsperger, 2009). Further exploration of alternative touch manipulations may clarify the mechanisms through which touch might enhance control. In the current manipulation, both the social (i.e., interpersonal proximity) and affective (i.e., pleasant) aspects of touch occurred during the handholding manipulation. Future research could test if it is the social or affective component of touch that contributes to increased control, or, alternatively, if both aspects act in unison to enhance control. Recent work indicates that affective touch could be investigated while minimizing the social interaction. Slow velocity tactile stimulation of the skin even in the absence of social context, for example, triggers pleasant experience (and regulates pain) through specific unmyelinated C tactile afferent fibers (Johansson & Vallbo, 1979; Krahé, Drabek, Paloyelis, & Fotopoulou, 2016). Future research could use these procedures to test if non-social aspects of affective touch modulate cognitive control. In addition to these extension studies, it would be valuable to conduct a direct replication of the current results in a second, larger sample. Although we preregistered and collected a sample size powerful enough to detect even relatively small effect sizes, many p values in the current study were in the .01 to .05 range. Although these results are significant at the a priori alpha levels, increasingly robust and precise estimates of effect size could be achieved by collecting a larger sample in a future replication.

Besides social and affective influences of interpersonal touch, motor-priming mechanisms might be suggested to account for the observed effects. By always engaging the left hand of the active participant, our interpersonal touch manipulation perhaps created a bias for the left response (i.e., the frequent stimulus), that, in turn, created a larger surprise signal to errors. Although it is certainly crucial to consider such low-level influences on our results, we think that this motor priming account is not likely to explain the effects observed in our study. The canonical feature of motor priming is a change in the overt motor response. People are often faster and more accurate if the correct motor response is primed by a lateralized source of bias, and slower and less accurate if the incorrect response is similarly biased by a spatial cue. Consequently, a motor-priming account would predict faster responses to the frequent "go" stimuli and higher error-rates for the infrequent "no-go" responses during handholding in our inhibitory control task. In our study, however, we observed no direct behavioral differences between conditions, and, if anything, our indirect effects tests show the opposite effect where control improves under interpersonal touch. Nevertheless, although we find no evidence directly supporting the presence of a motor-priming confound, this absence of evidence cannot completely rule out a more subtle motor confound manifest only in the ERP results. Further testing with varying control conditions (e.g., holding an innate object) could serve not only to even more definitely rule out low level confounds but would also allow further exploration of the specific aspects of touch that modulate cognitive control (e.g., relationship type, social proximity, affective processing) and shed light on the mechanisms by which interpersonal touch enhanced/facilitates cognitive control.

Finally, at first sight it appears that our results are discrepant with other neuroscience investigations in which interpersonal touch during the threat of electric shock was associated with reduced activation in neural areas commonly implicated in cognitive control (Coan et al., 2006, 2017). However, it seems likely that the effects of interpersonal touch might vary by context—handholding might have a different influence during overwhelmingly negative contexts (i.e., threat of electric shock) compared to goal-directed and cognitively demanding situations (e.g., inhibitory cognitive control). Although the sense of social support and interpersonal connection initiated by touch might soothe during overwhelmingly negative experiences, the same signal of social proximity might have a more encouraging and motivational effect during goal-directed activities, such as cognitive control. Future work should explore not only the influence of interpersonal touch across contexts, but also the effects of touch in cognitively demanding contexts that are also negatively valenced (e.g., control tasks in which errors are punished; Riesel et al., 2012; Saunders et al., 2015b).

Conclusion

Moving beyond the established benefits of touch for emotion and stress regulation, our findings are the first to suggest that touch enhances the neural monitoring processes that underlie flexible goal-directed behavior. These results open exciting avenues for future research investigating the role of social/interpersonal influences on a range of effortful, but goal-relevant, cognitive processes.

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