Title: Bootstrapping Agency: How Control-Relevant Information Affects Motivation

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Introduction

Registering co-variation in the environment can be highly functional by facilitating the learning of cause and effect relations. Perhaps more importantly, registering a subset of such changes that are in tight contiguity with one’s motor commands may enable the learning of valid causal relations between one’s behavioral repertoire and changes in the environment (i.e., the effects of its actions). For instance, it is only after infants have learned the effects of their actions can they voluntarily manipulate the environment (Hauf, Elsner & Aschersleben, 2004).

Such reasons (and others) led various researchers to hypothesize that exercising control over the environment is valuable to the organism and hence *is motivating in and of itself* (Burger & Cooper, 1979; Kelley, 1971; White, 1959; DeCharms, 1968; Eitam & Higgins, 2010; Eitam & Higgins, 2014; Higgins, 2012; Leotti, Iyengar, & Ochsner, 2010). However, only recently was the effect of ‘control’ on response selection (as 'having an effect') experimentally tested while controlling the valence of the effect (Eitam, Kennedy & Higgins, 2013; Karsh & Eitam, 2015a; see also, Karsh & Eitam, 2015b). Specifically, as we elaborate further below, Karsh and Eitam (2015a) recently showed that merely ‘having an effect’ facilitated both the speed and frequency of action selection independent of the valence of the effect (the ‘outcome’).

The current research aims to firmly establish that the impact of ‘having an effect’ on response selection is indeed due to the ‘effect’ being informative about the organism’s control over the external environment. To do so, we test the influence of factors previously shown to influence both ‘implicit measures’ of agency and people’s explicit judgment of control on different stages of action selection.

This research is based on the progress made in the last two decades in mapping the information that is important for one's sense of agency (e.g., 'I did X') - where the sense of agency is defined as *the feeling or judgment of being in control over the internal or external environment*.

As will be discussed below, close spatial and temporal contiguity between actions and effects were established as important factors for one's sense of agency, both independent of and in association with the conscious attribution of control to self (as well as a multitude of other expectations that affect such inferences or attributions; Blakemore, Frith & Wolpert, 1999; Haggard, Clark & Kalogeras, 2002; Franck, Farrer, Georgieff, Marie-Cardine, Dalery, d'Anato, Jeannerod, 2001; Sato & Yasuda, 2005; Weiss, Tsakiris, Haggard, Schutz-Bosbach, 2014; Dogge, Schaap, Custers, Wegner & Aarts, 2012; Dijksterhuis, Preston, Wegner & Aarts, 2008).

To form our hypotheses regarding the loci of influence of information about one's control in action selection, we build on our recently published control information-based response selection framework (See Figure 1; Karsh & Eitam, 2015b). Thus, a second goal of the current study is to test the predictions of the control-based response selection framework.

Objective Factors and Explicit Judgments of Control

The sense of agency has been recently described using a multifactorial model (Synofzik, Vosgerau & Newen, 2008), by which the mind integrates control information from both 'conceptual' (one's knowledge) and pre-conceptual sources (e.g., the motor control system). Accordingly, one route by which agency can be determined is through information generated by the motor control system (Blakemore, Frith & Wolpert, 1999; Wolpert & Flanagan, 2001; Blakemore,Wolpert & Frith, 2000; Blakemore & Frith, 2003). Briefly, the 'comparator model' account for motor-based computation of agency suggests that a representation of the predicted sensory consequence (generated using an 'efference copy' of the relevant motor command) is compared with a representation of the actual sensory feedback. A mismatch between the predicted and actual sensory feedback generates a negative sense of agency. Importantly, sensory-motor mismatches are not always available for consciousness (Jeannerod, 2006).

Blakemore, Frith and Wolpert (1999) found that the sensation resulting from our own actions is attenuated compared to externally (non-self) caused sensation. The authors used the comparator model as an explanation for this phenomenon; namely, that predicting the above mentioned sensory prediction of a motor plan attenuates (i.e., is subtracted from) the phenomenal sensation of self-generated stimulation. Following this theoretical link, and other studies that applied this model (mentioned above), sensory attenuation is today considered to be a pre-conceptual (i.e., motor system-based) marker of positive computation of agency. Most relevant to the current study is that when the spatial or temporal contiguity between actions and effects was weakened (e.g., by temporally lagging the action's effect; Blakemore et al., 1999), sensory attenuation decreased.

A second phenomenon that is considered to index a positive motor-based computation of agency is the temporal binding effect—the subjective perception that an action and a consequent effect occurred closer together in time than they actually did. Importantly, as in the case of sensory attenuation, the temporal binding effect was also decreased when the effect was temporally delayed (Haggard, Clark & Kalogeras, 2002).

It should be noted that both temporal binding and sensory attenuation effects were also found to be influenced by relevant expectations about the actions and their effects and other control-related beliefs (Desantis, Roussel & Waszak, 2011; Desantis, Weiss, Schulz-Bosbach &

Wsazak, 2012). Therefore, as is the case in most measures used in empirical psychology, they are not ‘process pure’, reflecting exclusively the outcome of a comparator. What is important for the current study is that both factors are seemingly important for motor-based computation of agency and *can* be made without being accessible to consciousness.

A second route through which a positive sense of agency can be made (“I did X”) is through a comparison between a conceptual representation of an effect (a thought, expectation or intentional state) and an observed event (Wegner & Wheatley, 1999; Aarts, Custers & Wegner, 2005), *regardless of any actual motor command*. Following this conceptual (if not necessarily conscious) route, when no other plausible agents are identified, an observed effect that is consistent with a preceding thought may lead people to infer that they caused the observed effect.

The latter kind of agency attribution is usually measured by soliciting participants' explicit control judgments with considerable variation between the exact wording and focus of the probes (e.g., "I was the one that produced X"; Sato & Yasuda, 2005; "How much control did you feel?" Wegner, Sparrow & Winerman, 2004; Metcalfe & Green, 2007). Key to the current study, this route to a positive judgment of agency does not *necessitate* adherence to the factors to which the comparator is sensitive (e.g., tight temporal and spatial contiguity of action-effect). Instead, it depends on one's content of thought, as well as other factors influencing attributions of causality (Wegner & Wheatley, 1999). For example, the effect of priming a specific thought (a color) on control judgments was observed even when the actual thought and effect (prime congruent color) were separated by more than 1000ms (Aarts, Custers & Marien, 2009; see also Ebert & Wegner, 2010). Conversely, previous work has shown that lagging effects by less than 500ms after an action produces drastically reduced sensory attenuation (Blakemore et al., 1999) and intentional binding (Haggard, Clark & Kalogeras, 2002).

To summarize, one’s sense of agency can be decomposed into agency determination through the motor control system (unconscious) and by more conceptual forms of attribution to self (both conscious and unconscious), independent of any motor command. Importantly for the current study, ‘objective’ control-relevant information (e.g., temporal and spatial contiguity of action-effect) can influence action selection directly or indirectly (that is through their influence on explicit judgments of agency).

The Control-Based Response Selection Framework

Performing an action necessitates selection among candidate actions. The optional actions are represented with their predicted reward values, and the one with the highest predicted reward is selected (Redgrave, Prescott & Gurney, 1999). For instance, Samejima, Ueda, Doya and Kimura (2005) showed that the striatum represents an action’s predicted reward value, and in this manner determines response selection. Following this process, a response option that is represented with a higher reward value compared to the others is selected more rapidly (Brown & Bowman, 1995) and more frequently (Samejima et al., 2005). Consistent with the above perspective and reflecting the ‘what to do’ (vs. ‘how much’) aspect of motivation (Frank, 2011; Graybiel, 1995) – we treat ‘motivation’ as the to-be-explained or observed outcome of response selection.

Although most studies on the influence of the brain’s “reward system” on action selection focus almost entirely on positively valanced (hedonic) outcomes (e.g., food or money), some work does suggest that high action-effect contingency (Behne, Scheich and Brechmann, 2008) and high perceived control (Tricomi, Delgado and Fiez, 2004; Lorenz et al., 2015) also activates the brain’s reward-related circuits (e.g., striatum). Moreover, it seemingly does so regardless of the outcome's valence. Recently, Eitam et al., (2013) and Karsh and Eitam (2015a) showed that if one's actions are followed by a seemingly neutral perceptual effect both the speed and frequency of responding increases. This was demonstrated using two different tasks and is consistent with the above neurocognitive framework if own-action effects were internally rewarded.

In Eitam et al's (2013) study (Exp. 1, 2 and 3), participants' reaction time was shorter when perceptual effects immediately followed their response compared to when participants did not have such an effect. In one of the experiments in that study (Exp. 3), the temporal contiguity between an action and the effect was manipulated by having the effect occur either immediately or after a 600 millisecond lag. This experiment replicated the facilitating effect of 'having an effect' on reaction time but only when the effect immediately followed the action.

A caveat to Eitam and colleagues' (2013) study was that action effects were given only when participants responded correctly to the task and hence the possibility that performance feedback also influenced response times could not be firmly ruled out. To dissociate the information about one's control over the environment from the information the effect conveys about one's task performance, Karsh and Eitam (2015a) designed a new task that required participants to freely and randomly select and press one of four response keys on the appearance of a cue. As there was no correct response in this task, effects were completely irrelevant to participants' task performance (in fact, they were disrupting). The study (Exp. 1) found that while participants, as they were instructed, seemingly attempted to respond "randomly" (i.e., they attempted to match the probability of emitting the four responses; Bar-Hillel & Wagenaar, 1991), they still tended to select the keys associated with a higher chance of causing an effect more frequently than those associated with no chance of causing an effect. This bias in the selection of effector (e.g., the finger), actually *damaged* their task performance (as their responses were less random). In addition, the results (Exp.1) replicated Eitam et al.'s (2013) finding of shorter reaction times in the condition where all responses led to a high probability of causing an effect (*vs*. never causing one).

Karsh and Eitam (2015a) also found that the accuracy of participants' explicit control knowledge (i.e., their awareness of the contingency between action and effects) was associated with the frequency of responding with the finger that most probably led to an effect. Conversely, participants' reaction time was associated only with the actual number of effects they received and not by their explicit control knowledge.

Based on the findings reviewed above, we suggested that own action effects are rewarding and hence influence further response selection as described in the control-based response selection framework (Karsh & Eitam, 2015b, see Figure 1).

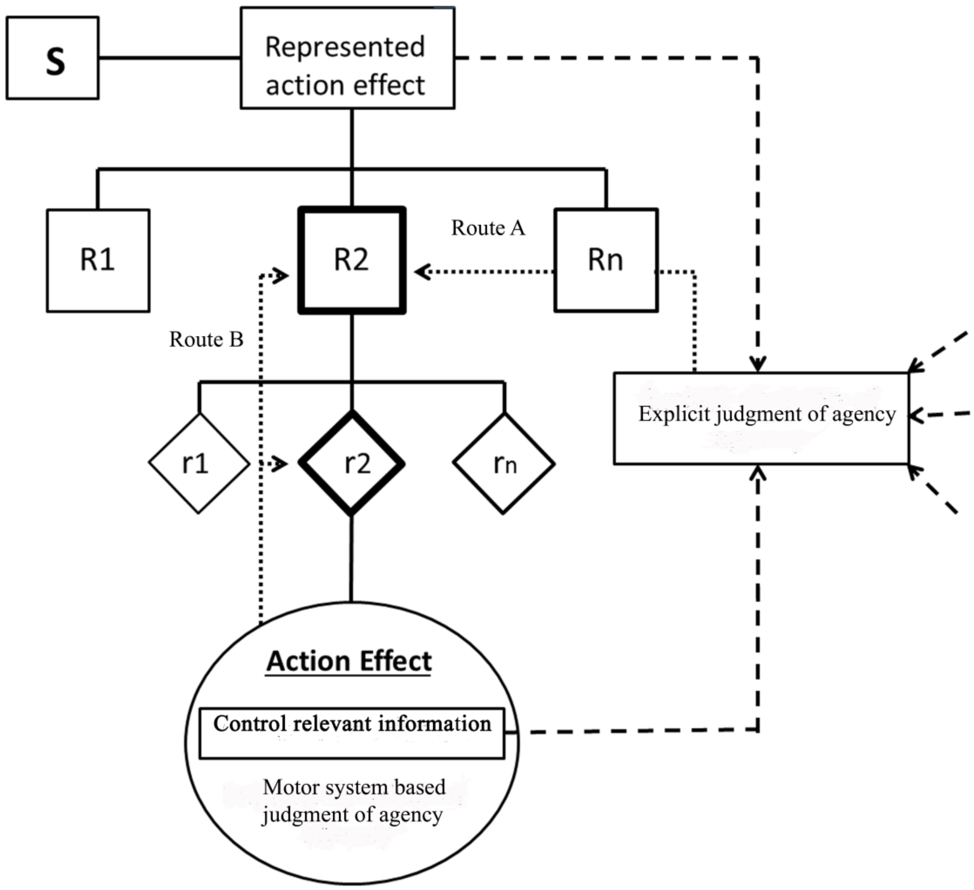

Fig. 1. A schematic illustration of the control-based response selection framework. The illustrated processing and reinforcement paths begin with any event, external or internal, which elicits a representation of an intended action effect (marked by the letter 'S'). The upper rectangles designate higher-level response options ($R_1 \ldots R_n$; e.g., optional fingers) and the lower rectangles designate lower level (e.g., motor) response parameters ($r_1 \ldots r_n$). The width of the rectangles' borders depicts the magnitude of a response's predicted control value (and hence reward). In this context, the response option with the highest predicted control value is selected. Dashed arrows depict control information relevant for an explicit judgment of agency (e.g., a non-match between intended and actual effect and ex motor-system information such as desires and beliefs). The dotted arrows depict control value from explicit judgments (right; Route A) and other (left; Route B) 'objective' control relevant information (independently of their influence on explicit judgment); control value is fed back to the action control system, updating responses' control predicted value, which will in turn, together with outcome predicted value (described elsewhere), determine further response selection. The figure is adapted from Karsh & Eitam, 2015b © By permission of Oxford University Press.

Consistent with previous claims about consciously available and unavailable stages of action selection (Badre, Kayser & D'Esposito, 2010; Haggard, 2005; Carota, Desmurget & Sirigu, 2009), we (Karsh & Eitam, 2015b) suggested that the frequency of a specific response (due to the selection of the effector or 'what to do', which can be consciously accessible; e.g., Haggard, 2005) could be influenced by both explicit judgments of control and their possible outcome: consciously accessible knowledge of one's control (e.g., the level of action-effect contingency awareness) (see Route A in Figure 1) and by the often inaccessible (Haggard, 2005), 'comparator driven' computations of agency (see upper part of Route B in Figure 1). However, only 'comparator driven' computations of agency can affect the speed of responding, which (given our experimental setting) is an index of a lower stage of response selection (e.g., selection of actual motor parameters; see lower part of Route B in Figure 1) that is consciously inaccessible (Carota, Desmurget & Sirigu, 2009).

The Current Research

The current study was designed to test the predictions of the control-based response selection framework mentioned above. Specifically, the purpose of the current study was to test whether factors—temporal and spatial contiguity—that are important for motor-based computation of agency over a perceptual change in the environment (i.e., that deem the event an 'instance of control') modulate the influence of this perceptual change on further action selection. In addition, given that different stages of response selection (i.e., the selection of the effector and the selection of movement parameters) differ in their potential accessibility to conscious awareness, we were interested in how such control-relevant information affects different stages of response selection both directly (Route B in Figure 1) and indirectly (Route A in Figure 1) through their influence on explicit control judgments.

In Experiment 1a, we aimed to replicate the effect of manipulating *temporal* contiguity on reaction time. To do so, we used the same task used by Eitam et al., (2013; Experiment 3), mentioned above. In Experiment 1b, we aimed to replicate and generalize the findings of Experiment 1a (and also Eitam et al., 2013-Exp.3) using a different ('free' choice) task that better dissociates control feedback (having own-action effect) from feedback about task performance. In Experiment 1c, manipulating the temporal contiguity at the level of the response option allowed us to measure its effect on both the speed and frequency of response selection, the latter being a classic measure of reinforcement. In Experiment 2a, we again used Eitam et al.'s (2013) task to ask whether manipulating the *spatial* contiguity between actions and their effects will also reduce the impact that 'having an effect' has on reaction time. Finally, in Experiment 2b, we used a modified version of this task to differentiate between two possible explanations for the findings from Experiment 2a; namely, the spatial *contiguity* between the target-object and the effect, and the spatial *predictability* of that effect.

Experiment 1a: The Effect of Temporal Contiguity on the Speed of Action Selection – A Cued Response Task

Method

Participants

One hundred and two undergraduate students[1] [64 females, Age (M=24.86, SD=4.46)] from the University of Haifa participated in the experiment in exchange for course credit or 20 Shekels (~$6).

Stimuli and Procedure

[1] The sample size in Exp.1a, 1b, 2a and 2b was ~25 per condition. The sample size was determined based on a large number of previous experiments from our lab using this task (see also, Eitam et al., 2013).

Participants faced a computer screen and placed their fingers on four designated response keys ('S', 'D', 'H' and 'J') on a standard PC keyboard. A trial began with the presentation of a colored circle (53 pixels in diameter) in one of four possible horizontal locations at the top of the game window (9.5cm X 10cm); on appearance, the circle rapidly descended in a vertical downward path. Participants were instructed to 'stamp' the circles as they appear on the screen by pressing the relevant (spatially and color coded) key. From the appearance of the circle, participants had approximately 1300 ms to respond (until the circle disappeared at the bottom of the screen)[2]. A fixed time interval of approximately 1450 ms was maintained between the onset of one stimulus (an appearance of a circle) to the next. This held regardless of participants' reaction time.

A perceptual effect followed a participant's correct response (the circle changed its color to white for 100ms and then disappeared; phenomenally experienced as a flash). The task consisted of 12 blocks with 30 trials per block. There was no indication that a block had ended.

Participants were randomly assigned to one of four between-subjects conditions: an Immediate effect (standard) condition in which the effect occurred immediately after a correct response; a Short lag effect condition in which the effect occurred 300 ms after a correct response; a Long lag effect condition in which the effect occurred 600 ms after a correct response; and a No-effect (standard) condition in which no effect occurred and the colored circle simply appeared to continue its descent until disappearing at the bottom of the game window. After completing the task, participants responded to a computerized self-report questionnaire using a continuous scale of endorsement running from 1 (not at all) to 100 (very much). The

[2] As in Eitam et al., (2013; Experiment 3), we extended the duration of the game window from the standard 850ms (Eitam et al., 2013; Experiment 1) to 1300ms to allow sufficient time for the lagged effect to appear.

questionnaire probed their perceived control, as well their enjoyment and perceived successes in the task.

Based on our previous findings (Eitam et al., 2013; Karsh & Eitam, 2015a), we expected that reaction time would be shorter in the Immediate effect condition versus the No-effect condition. Crucially, based on the previous work cited above we also expected that reaction time would be shorter in the Immediate effect condition compared to the Lagged effect conditions. Such a pattern of results would reaffirm that the influence of 'having an effect' on (the speed of) further response selection is sensitive to very close temporal contiguity just as other 'comparator' based effects (e.g., sensory attenuation) were shown to be.

Results and Discussion

Before analyzing the data we used these filters in the following order: participants with more than 50% incorrect responses (one participant), responses that were either above 700ms or below 200ms (4048/36720=~11%)[3], incorrect responses (1407/36720 = ~3 %), and trials that deviated from their condition's mean by at least 2 standard deviations in either mean reaction time and percent correct (2321/36720=~6%). Filtered responses were removed and not analyzed further.

Performance: Reaction Time

[3] We used this filter in all experiments to equate the RT filters for the two different tasks we present (Experiment 1a 1b and Experiment 1c) with the filter applied by Karsh and Eitam (2015a) to a task that used a 700ms-long response window. Note that the removal of the filter does not change the pattern of results. For instance, In Experiment 1a, the RT difference between the immediate and the long lag effect conditions with the RT<700 filter (Immediate: M=405.97, SD=42.77; 600ms Lag: M=472.73 SD=61.85) and without (Immediate: M=419.53, SD=61.02; 600ms Lag: M=483.54 SD=75.8) is practically the same (*d*=66.76 and *d*=64.01, accordingly).

As a behavioral proxy for the speed of action selection, we analyzed participants' reaction times (Pullman, Watts, Juncos, Chase & Sanes, 1988). A one-way between-participants ANOVA with Effect condition (No effect vs. Immediate vs. Short lag vs. Long lag) shows that the effect of Effect condition was reliable ($F_{3, 91}$=8.25, root *MSE*=49.31, p<.05; see Fig. 2).

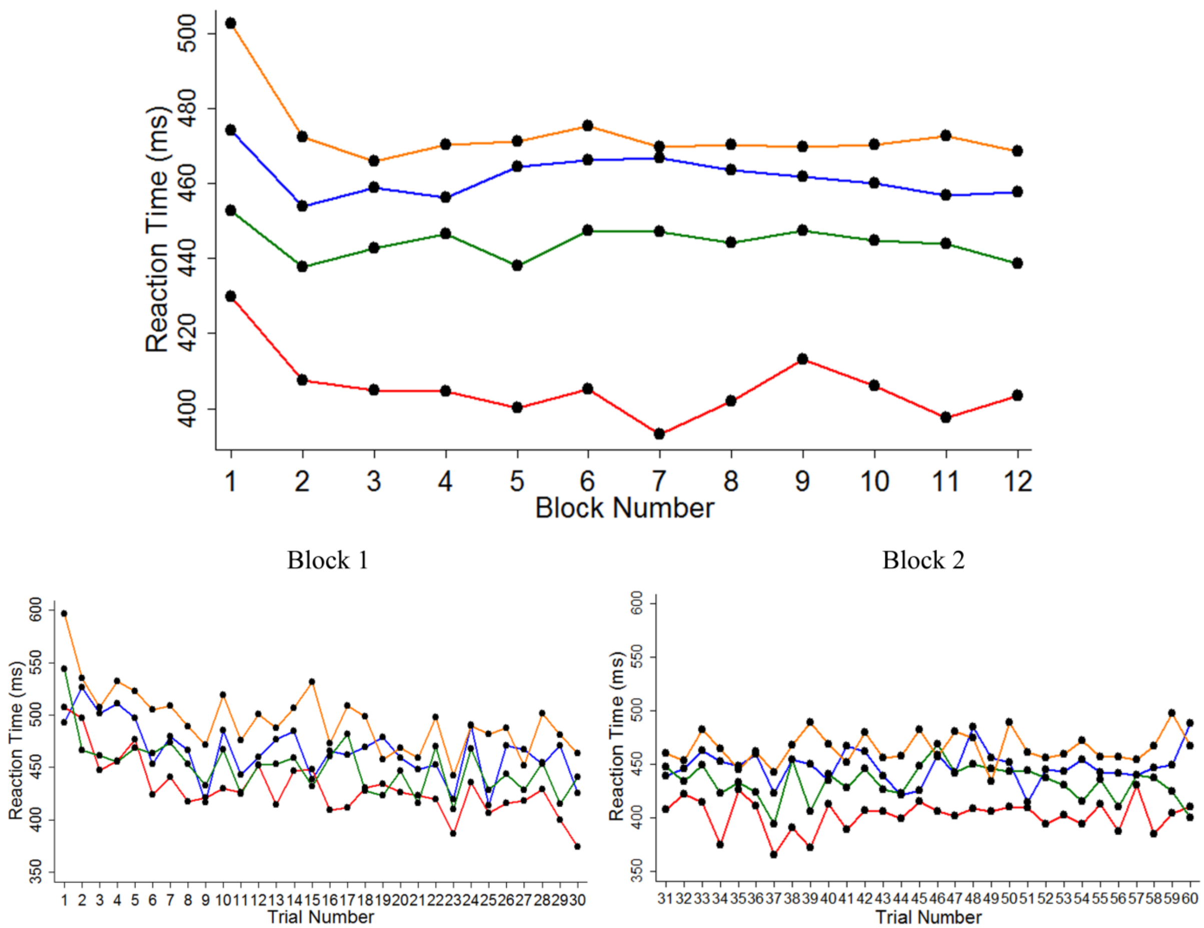

Fig. 2. Experiment 1a: Reaction time. (Upper) Mean reaction time by block (30 trials) and by experimental condition. (Bottom) Mean reaction time by trial in the first two blocks and by experimental condition. As can be seen, the seemingly immediately observed pattern stabilizes only on the final trials of the first block.

A planned contrast supports the conclusion that participants were faster in the Immediate condition (*M*=405.97, *SD*=42.77) versus the No-effect condition (*M*=461.06, *SD*=54.26) [$F_{1,}$

$_{91}$=14.66, p<.05, d=1.12, CI_{95} (26, 83)]. More importantly, participants were also faster in the Immediate effect condition than in both the Long (M=472.73, SD=61.85), [$F_{1, 91}$=21.52, p<.05, d=1.25, CI_{95} (35, 98)] and Short lag (M=443.8, SD=35.52) [$F_{1, 91}$=7.21, p<.05, d=.96, CI_{95} (15, 60)] conditions. The contrasts between the Long lag and the No-effect conditions [$F_{1, 91}$=.64, p=.42, CI_{95} (-46, 22)] and between the Short lag and the No-effect conditions [($F_{1, 91}$=1.47, p=.22, CI_{95} (-9, 43)] were not significant.

Explicit Judgment of Agency

Confirming that the effect is highly sensitive to action-effect temporal contiguity, we proceeded to explore participants' perceived control (measured by the item “How much in control did you feel during the task?”); this enabled testing whether objective factors affect action selection through explicit control judgment (Route A in Figure 1) or independently of them (Route B in Figure 1) . First, we tested whether having an effect influenced participants' perceived control. Unsurprisingly, a one-tailed t-test between the Immediate and No-effect conditions revealed that participants' *perceived* control was higher (albeit the marginal significance) in the Immediate effect condition (M=52.66, SD=27.85) than it was in the No-effect condition (M=37.39, SD=35.3) [t_{45}=-1.65, p=.052, d=.48, CI_{95} (-33, 3)]. [4]

Of more interest is whether and how increasing the lag between actions and effects influenced participants' perceived control. A planned contrast (Immediate *vs*. Short lag and Long lag effect conditions) revealed that (in contrast to reaction time), participants’ perceived control did not differ numerically between the Immediate effect condition and both the Short lag

[4] The fact that ~92% of the parameter values suggested by the confidence interval are in the predicted direction captures the effect of immediate effect on judgments of control in another manner (cf. Cummings, 2013). We also performed a Bayesian calculation using a half normal prior (Dienes, 2008) which generated a Bayes Factor of 2.14 meaning that although there is anecdotal support for an effect of the immediate effect on explicit judgment of control the current experiment is insensitive.

(*M*=53.92, *SD*=33.52) and Long lag (*M*=49.17, *SD*=27.36) effect conditions (F<1). This means that participants' perceived control was sensitive to having an effect per se and not to its temporal contiguity with the action. This is consistent with previous measurements of "accepted lags" for judgments of authorship (did I do it?), which were shown to be positive even after 700ms lag between actions and effects (e.g., Ebert & Wegner, 2010).

Importantly, participants' perceived control did not correlate with their reaction time (r=.04, p=.63). The pattern of findings supports the proposal of (at least partially) independent processes of agency: explicit judgment of control and motor-based computation of agency (see also Synofzik et al., 2008; David, Newen & Vogeley, 2008; Moore, Middelton, Haggard & Fletcher, 2012); further, these processes may have differential sensitivity to 'objective' control-relevant information (i.e. very close [<300ms] temporal action-effect contiguity; see also, Karsh & Eitam, 2015a; 2015b).

In addition, we measured participants' perceived success and enjoyment during the task (see Supplemental Materials for observed differences between conditions and their correlation with participants' reaction time). Importantly, neither of these correlated with reaction time.

To summarize, the behavioral results show that temporal contiguity reliably modulates the effect of having an effect on the speed of action selection (cf. Eitam et al., 2013). Additionally, the results show that in the context of our task at least and in contrast to the effect of temporal lag on action selection; perceived control is sensitive only to having an effect and is not affected by subtle lags of action-effect (see also Experiment 1b). Consistent with the control-based response selection framework, the findings support the proposal that control relevant factors affect (the speed of) action selection directly rather than through explicit judgments of control.

Given these substantial implications, the goal of Experiment 1b was to test whether this pattern generalizes to a very different task that involves a 'free' choice of response key. Two additional benefits of this task are that it better dissociates between control and outcome feedback and affords measurement of reinforcement as a change in response frequency alongside reaction time (Karsh & Eitam, 2015a).

Specifically, beyond generalization of the pattern of results found in Experiment 1a (essentially a replication of Eitam et al., 2013- Exp.3), Experiment 1b was conducted to support our conclusion that the results were not due to the ‘effect’ carrying information about task performance. For this purpose, we used a modified version of the task we used in Karsh and Eitam (2015a) in which participants’ were to select responses randomly making the effect (objectively) completely irrelevant to their task performance.

Experiment 1b: The Effect of Temporal Contiguity on the Speed of Action Selection – An Un-Cued Response Task

Method

Participants

Forty one undergraduate students [25 females, Age (*M*=27, *SD*=4.98)] from the University of Haifa participated in the study in exchange for course credit or 20 Shekels (~$6).

Stimuli and Procedure

In Experiment 1 we used the task from Karsh and Eitam (2015a) with different conditions. Participants faced a computer screen and placed their fingers on four designated keys ('S', 'D', 'H' and 'J') on a standard PC keyboard. On each trial, a red circle (a response cue; 53 pixels in diameter) appeared at the center of the screen; participants were instructed to randomly choose and press one of four response keys whenever the red cue appears. Following a response, the red cue changed its color to white for 150 ms and disappeared until the end of the trial (an "effect", experienced as a brief flash). We further instructed participants that their (random) responses should "avoid any fixed or planned response sequences". Given people's lay understanding of randomness as probability matching (Bar-Hillel & Wagenaar, 1991), these instructions were shown to subtly control participants' response probabilities (Karsh & Eitam, 2015a).

From the onset of the response cue, participants had approximately 1300 ms to respond. Stimulus onset asynchrony (SOA; response cue to response cue) was approximately 2600 ms, regardless of participants' reaction time. Participants performed 10 practice trials followed by 180 experimental trials.

Participants were assigned randomly to one of two conditions. In the (standard) Immediate effect condition, the effect appeared immediately after each of the four relevant responses. In the Lagged effect condition, the effect appeared 450ms after each of the four relevant responses. As in Experiment 1a, we predicted that participants' reaction time would be shorter in the Immediate effect condition compared to the Lagged effect condition. In addition, as in Experiment 1a, we expected no difference in participants' perceived control between conditions, as perceived control was found to be less sensitive to such subtle temporal lags between actions and effects.

Results and Discussion

Before analyzing the data we used these filters in the following order: Irrelevant key presses (392/7380=~5%), responses longer than 700 ms or shorter than 200 ms (259/7380=~3%), and responses that deviated by more than two standard deviations from their condition mean RT

(415/7380=~5%). Responses associated with these filters were removed and were not analyzed further.

Performance: Reaction Time

Consistent with our prediction, a t-test revealed that reaction time was shorter in the Immediate effect condition (*M*=344.95, *SD*=18.62) than in the Lagged effect condition (*M*=366.17, *SD*=30.90) [t_{38}=2.66, *p*<.05, *d*=.83, CI_{95} (5, 37)]. This generalizes our conclusion that close temporal contiguity of action effect is necessary for an action effect to facilitate response selection; importantly, this holds even when the action effect is completely irrelevant to task performance.

Explicit Judgment of Agency

First, we tested whether inserting a temporal lag between actions and effects influenced participants' perceived control. Consistent with Experiment 1a, participants' perceived control did not differ between the Immediate (*M*=66, *SD*=26.41) and the Lagged effect (*M*=64.89, *SD*=18.21) conditions (t_{38}<1). We also probed for participants' causal attribution of the effects as being a consequence of their actions using an item similar to the one used by other researchers to measure one's sense of agency (Chambon and Haggard, 2012; Sato, 2009; Sato & Yasuda, 2005; Gentsch, Kathmann & Schutz-Bosbach, 2012): "How much did you feel your actions caused outcomes during the task?". No difference in participants' degree of causal attribution was found between the Immediate (*M*=71.61, *SD*=33.02) and the Lagged effect (*M*=68, *SD*=27.68) conditions (t_{38}<1) (but see Exp.2b). There was also no significant correlation between participants' perceived control (*r*=-.08, *p*=.59) or participants' causal attribution (*r*=-.23, *p*=.13) and their reaction time.

Experiment 1c: The Effect of Temporal Contiguity on the Speed and Frequency of Action Selection – A Non-cued Response Task

Method

Participants

Thirty five undergraduate students[5] [27 females, Age (*M*=24.51, *SD*=4.47)] from the University of Haifa participated in the study in exchange for course credit or 20 Shekels (~$6).

Stimuli and Procedure

In Experiment 1c we used a similar task to the one used in Experiment 1b with a number of required modifications. Action-effect temporal contiguity condition ([no lag] 0ms, 150ms lagged, 300ms lagged, and 450ms lagged) was *key specific* and was allocated in a counterbalanced manner (between participants) to the 4 response keys. This created a situation in which -- on one extreme -- was a key that always led to an immediate effect and on the other was a key that always led to a 450ms lagged effect. The action-effect lags of the two other keys middle. No mention of the effects was made in the instructions. As in Experiment 1b and given people's lay understanding of randomness as probability matching (Bar-Hillel & Wagenaar, 1991), instructing participants to respond randomly enabled us to use P(.25) as the baseline probability for pressing one of the four keys and measure both participants' response frequency on each key and their reaction time.

To assess and maintain participants' attentional engagement during the task, a blue triangle appeared nine times throughout the experiment instead of the frequent response cue (on

[5] In Exp. 1c (n=35), using a different (and less familiar) task, the required sample size was calculated with G-power software using the following parameters: Power=.85, Alpha=.05, Effect size=.5 (according to the difference in response frequency between the high probability key compared to the no-effect key in the Finger Specific Lagged Effect condition, Karsh & Eitam, 2015a-Exp.2).The recommended sample size was 31 per condition.

5% of trials). Participants were instructed to press the ‘Space’ key with their thumbs whenever a blue triangle appears.

After completing the task, participants responded to a computerized self-report questionnaire probing the degree of control they had felt during the task (using the item “How much in control did you feel during the task?”) and their key-specific action-effect temporal contiguity awareness. To measure the latter, participants were asked to place their fingers on the four response keys as they did when performing the task and to rank them according to the degree of the keys' action-effect temporal contiguity during the task (maximal to minimal) and, again, by the degree that the key enabled control (maximal to minimal). A correct answer received one point and thus participants' score could range from 0 (no awareness of temporal contiguity) to 8 (maximal awareness).

In addition, we measured participants' perceived adherence to the task goal to respond randomly and their self-reported intention to have an immediate effect. These measures allowed us to assess whether participants' erroneously perceived the immediate effect as indicating success in the task of being random (cf. Karsh & Eitam, 2015a). Given the contention that immediacy (close temporal-contiguity between action and effects) is an important factor for arriving at a positive judgment of agency, we again predicted that participants' reaction time would be shorter as a function of the number of immediate (but not lagged) effects they will receive. In addition, we hypothesized that explicit judgments of control will not be associated with reaction time.

Conversely, given previous indications that response frequency (e.g., which key or effector to respond with) may be more sensitive to consciously available considerations (Karsh & Eitam, 2015a), we wanted to test whether participants' choice of key would be affected by the temporal contiguity between action effects both directly and indirectly -- through their effect on explicit control judgments (see Figure 1 Routes A & B).

Results and Discussion

Before analyzing the data we used these filters in the following order: Irrelevant key presses (403/6300=~6%), responses longer than 700 ms or shorter than 200 ms (92/6300=~1%), and responses that deviated by more than two standard deviations from each participant's mean RT (314/6300=~5%). Responses associated with these filters were removed and were not analyzed further.

Performance: Reaction Time

First, we tested the correlation between the number of immediate effects participants received (as actual frequency of positive control feedback) and their overall mean reaction time in the task and found that as predicted, the more immediate effects participants received -- the faster their reaction time was (r=-.48, p<.05, see Fig.3). Importantly, no such correlation was observed between the number of 450ms lagged effects participants received and their reaction time (r=-.03, p=.84; see Fig.3). There was also no correlation between the number of 300ms and 150ms lagged effects participants received and their reaction time (r=.16, p=.33 and r=-.12, p=.48), respectively. We also simultaneously regressed participants' mean reaction time on the number of effects from each lag condition participants received [$F_{(4, 30)} = 3.32$, p<.05, R^2 =.30] and we found that only the number of immediate effects participants received during the task predicted their reaction time [p<05, β =-.61, CI_{95} (-6, -1)]; not the number of 150ms lagged effects [p=.1, β =-.37, CI_{95} (-4, .43)], 300ms lagged effect [p=.21, β =-.26, CI_{95} (-4, .98)] or 450ms lagged effects [p=.11, β =-.36, CI_{95} (-5, .65)].

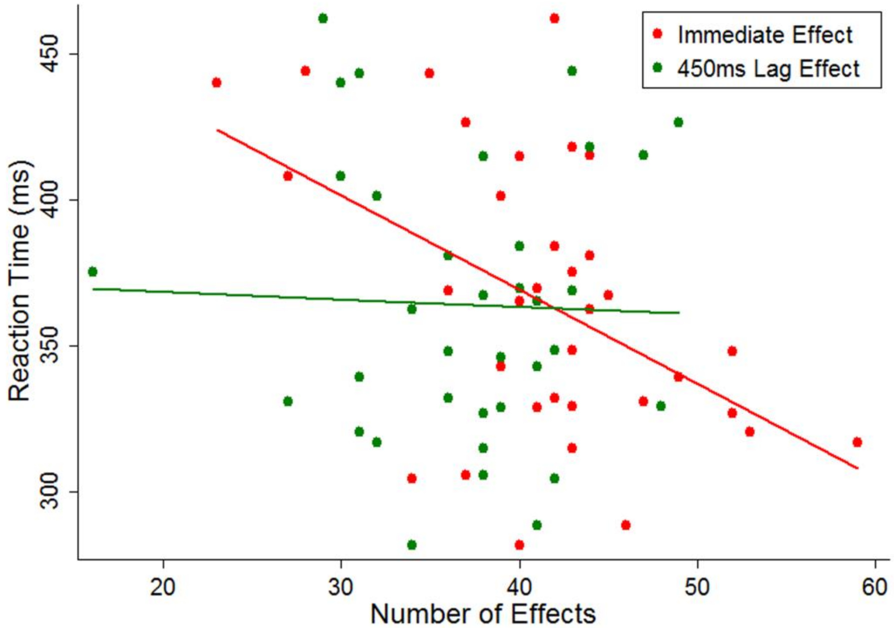

Fig.3. Experiment 1c: Reaction time as a function of the number of effects received. A scatterplot with fitted regression lines and participants' mean RT's as a function of the number of immediate (red) and 450ms Lagged effects (green) received shows that only the number of immediate effects correlated with reaction time.

These findings are consistent with Karsh & Eitam's (2015a) and suggest that the more immediate (but not lagged) effects participants received (i.e. positive control feedback) – the higher was their reward predicted value and hence the faster these responses were selected.

We next tested whether a less specific motivation-based story can explain the above pattern. Namely, that the shortening of reaction time as a function of the number of immediate effects a participant received is due to an increase in general task engagement rather than the facilitation of selection of specific responses or, is possibly influenced by both (cf. Karsh & Eitam, 2015a). Participants' reaction time to the rare attentional probe was positively correlated with their reaction time to the target cue (r=.52, p<.05) and was also negatively correlated with the number of immediate effects they received (r=-.33, p<.05).

This suggests that the more immediate effects participants received the more they were engaged with the task (cf. Karsh & Eitam, 2015a), hence there is some indication of a 'more general' motivating effect of having an effect. Our question though was whether this general motivation explains the facilitation in response which we argue is response (and effect) specific; the answer is negative – when reaction time to the target cue was simultaneously regressed on both predictors ($F_{2, 32}$=9.9, p<.05, R^2=.38), the number of immediate effects (amount of positive control feedback) predicted reaction time to the target cue [p<.05, β=-.34, CI_{95} (-4, -.28)] even after factoring out the relationship between reaction time to the target cue and reaction time to the attentional probe (as a proxy for general task engagement[6]), [p<.05, β=.41, CI_{95} (.04, .29)]. This suggests that the amount of positive control feedback affected response times over and above increasing participants' general attentional engagement – presumably by facilitating response selection.

Thus, consistent with the results of Experiment 1a and 1b and the control-based response selection framework, Experiment 1c confirms that close temporal contiguity between action and effects can influence a consciously unavailable stage of response selection (e.g., selection of motor paramters). Importantly, this holds even when participants 'freely' select their responses and after accounting for their general engagement with the task.

Response Frequency

In order to test whether participants' control-biased choice of keys is also moderated by the temporal lag, we modeled the logarithm of the ratio of the proportion of presses of each of the three keys with temporal lag and of the immediate effect key (our baseline proportion) using a Dirichlet distribution. This tests whether any of these ratios is statistically different from zero, which is the value that would be expected if all proportions were not different from the baseline

[6] The relationship between the two response times may also reflect other factors of course (e.g., individual differences in working memory capacity). The important point here is that it enables us to model, to some degree, all such factors and show that the locus of influence of control feedback is the motor representation of the responses that were associated with that feedback.

proportion. Using a Dirichlet distribution is necessary here as it best models our data which, being (multiple) probabilities ranges from 0 to 1, must all add up to 1 and hence are dependent as the selection of one response option would lower the probability of others being selected (see, Buis, Cox & Jenkins, 2006).

A planned contrast suggests that a linear pattern (see, Fig.4) best describes the relationship between the proportion in which a key was selected and temporal lag of the effect associated with it. Responses that delivered immediate effects were selected more often (*M*=.26, *SD*=.04) than responses that delivered 450ms lagged effects (*M*=.23, *SD*=.04) [*Z*=-2.21, *p*<.05 CI_{95} (.005, .049)]. No other differences in response proportions were observed [150ms lagged effect (*M*=.25, *SD*=.05); 300ms lagged effects (*M*=.24 *SD*=.05)].

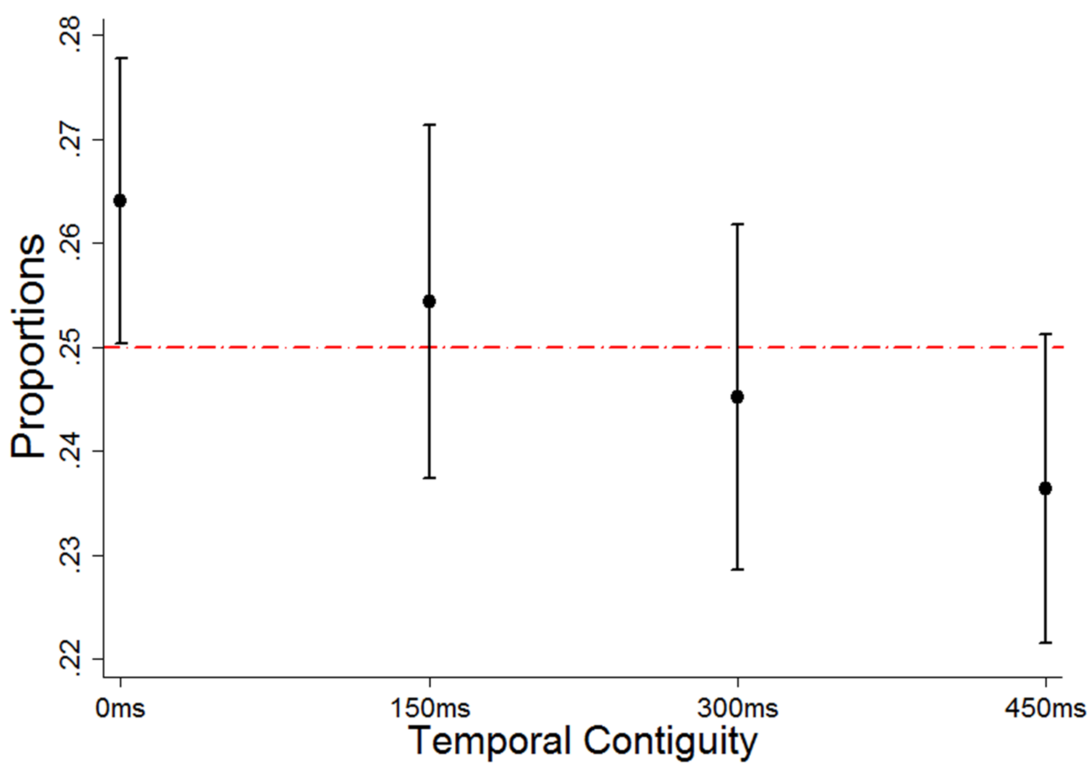

Fig. 4. Experiment 1c: Response frequency. Proportion of responses by each Key-specific lag condition (0ms, 150ms, 300ms and 450ms). The red horizontal line indicates chance level (.25). Participants chose the key that delivered immediate effects more often than the key that delivered 450ms lagged effects.

The findings support the conclusion that response frequency is too affected by the temporal contiguity of action effect (Karsh & Eitam, 2015a; 2015b). We then turned to examine the hypothesized dissociation between the direct (see Figure 1 Route B) and indirect influence (see Figure 1 Route A) of control relevant factors (e.g., temporal contiguity) by analyzing the effect of participants' perceived control and temporal contiguity awareness on action selection.

Explicit Judgment of Agency

Based on the results of Experiments 1a and 1b, we predicted that perceived control would not correlate with reaction time. As expected, no such correlation was found (r=.02, *p*=.88). Importantly, perceived control also failed to correlate with the number of presses on the key that delivered immediate effects (r<.01. *p*=.97). This pattern strengthens our conclusions that (1) perceived control is less sensitive to subtle temporal lags between an action and possible effects (i.e. the conscious perceiver is less sensitive to temporal lag as a factor of control, at least with the current wording of the question) and (2) that perceived control is not reliably associated with speed of action selection.

In addition, we measured participants' temporal contiguity awareness. As can be seen in Table S1 and as compared to knowledge about key-specific probability of the effect (Karsh & Eitam, 2015a-Exp.1), participants' temporal contiguity awareness was relatively low (only one subject gained a perfect score)[7]. More importantly and as is the case for perceived control, the

[7] A t-test comparing the difference between participants' explicit control knowledge of action-effect temporal contiguity (the current experiment) and action-effect contingency (Karsh & Eitam, 2015a – Exp.1) supports the

degree of knowledge of the temporal contiguity between actions and effects did not correlate with participants' reaction time (r=.05, p=.77); moreover, explicit knowledge of temporal contingency did not correlate with the number of presses on the key delivering immediate effects (r=.09, p=.57).

These findings suggest that – in the case of subtly manipulating temporal lag between actions and effects – *both* response facilitation and biasing of the relative proportion of presses towards the more immediate effect keys were a result of consciously unavailable process of response selection.

This is important as, we have previously shown (e.g., Karsh and Eitam; 2015a), response frequency (in contrast to reaction time) *can* be influenced by explicit control judgments (and perhaps by other explicit considerations too; e.g., exploratory motives, hypotheses testing). However, in the current setup, no such association was detected; seemingly due to the relatively high *phenomenal* similarity between the immediate and lag conditions (and given the demonstrated low sensitivity of uninstructed human observers to such lags, see Table S1). This suggests that regarding this more ‘high level’ measure of response selection, a hierarchy may exist in that direct influences of various control relevant factors surface only when the indirect ones are weak or random. We develop this point further in the General Discussion.

Finally, to rule out the possibility that participants erroneously perceived the immediacy of the effect as indicating success at responding randomly (i.e., as it being outcome or performance feedback), we tested the correlation between their self-reported evaluation of responding randomly and their self-reported intention to select the finger that would produce an

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conclusion that participants were more sensitive to (i.e. had better explicit knowledge of) action-effect contingency (M=3.77, SD=2.31) than to temporal contiguity (M=2.51, SD=1.00) [t_{110}=2.79, p<.05, d=.7, CI_{95} (.36, 2)].

immediate effect during the task. We found no such correlation (r=-.02, p<.89). Thus, participants seemed not to interpret the immediate effect as being positive performance feedback, which is also consistent with their low temporal contiguity awareness.

The findings from Experiments 1a-1c lend substantial support to the conclusion that temporal contiguity is an important control relevant factor and is hence crucial for (action) effects to influence further response selection. They also suggested that close temporal contiguity has a direct effect on both levels of action selection – unmediated by explicit judgments of control. In Experiment 2a and 2b, we focus on a second control factor that has been previously shown to reliably influence motor-based computation of agency—spatial contiguity/predictability (Blakemore, Wolpert & Frith, 1999; Farrer, Bouchereaua, Jeannerod & Franck, 2008). Specifically, we tested whether the spatial contiguity between actions' intended and actual effects and spatial predictability influence action selection.

Experiment 2a: The Effect of Spatial Contiguity and Spatial Predictability on the Speed of Action Selection

Method

Participants

One hundred and forty eight students [94 females, Age (M=24.08, SD=3.58)] from the University of Haifa participated in the study in exchange for course credit or 20 Shekels (~$6).[8]

Stimuli and Procedure

The experiment used a modified version of the task described in Experiment 1a. From the moment the circle appeared, participants had approximately 850 ms to respond (until the circle

[8] The demographic information of 10 participants was lost due to a technical problem.

disappeared at the bottom of the screen). Regardless of participants' response speed – the time interval between one stimulus' onset (the appearance of a circle) and the onset of another (SOA) was fixed at approximately 1300 ms. Participants were assigned to one of six between-subjects conditions (see Fig. 5; a (standard) *Overlapping effect* condition in which the perceptual effect fully overlapped the target circle; a (standard) *No-effect condition* in which no effect appeared after a response; a *Half-overlapping effect condition* in which the effect appeared randomly in one of four locations, partially (half) overlapping the target stimulus locations; a *Touching effect condition* in which the effect appeared randomly in one of four locations, all just 'touching' the target circle; and a *Distant effect condition* in which the effect appeared randomly in one of four locations ~2.4 cm away from the target.

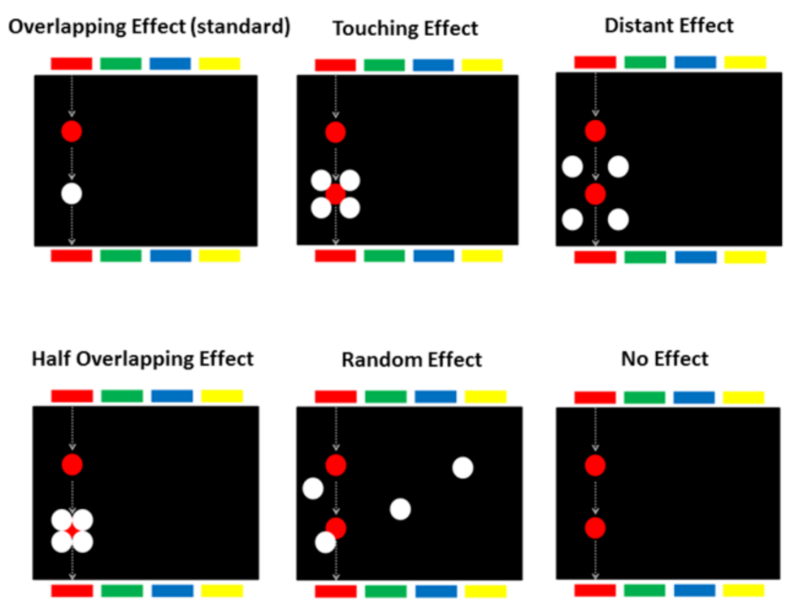

Fig.5. An example of possible locations of the effect in each of the 6 experimental conditions. In the Overlapping effect (standard condition) the effect (white circle) fully overlapped the response cue (red circle) when a relevant response was made. In the No-effect condition (standard condition) no effect appeared after a response. In the Touching effect condition the effect could appear in *one* of four locations (randomly determined), "touching" the

response cue when a relevant response was made. In the Distant effect condition the effect could appear in one of four locations (randomly determined), ~2.4cm from the response cue when a relevant response was made. In the Half-Overlapping effect condition the effect could appear in one of four locations (randomly determined), half-overlapping the response cue when a relevant response was made. In the Random effect condition the effect could appear anywhere on the game window when a relevant response was made (randomly determined).

Note that in these latter three conditions, spatial *predictability* was constant with a 25% chance of predicting the location of the next effect (that could appear in one of four locations) while in the Random effect condition the chance of predicting the location of the next effect was practically nil.[9] As a first attempt to differentiate between whether the effect's spatial distance from the target, its spatial predictability or both (Blakemore et al., 1999; Hughes, Desantis, Waszak, 2013) would modulate the effect of 'having an effect' on response selection we also used a *Random effect condition* in which the effect appeared in random locations on the game window (12cm X 16cm) (an effect that is spatially unpredicted through the internal model). Note that in this design the effect in the Random effect condition differed from the effect in the Overlapping effect condition in *both* predictability and distance from the target cue.

Participants completed 180 experimental trials and then filled a computerized self-report questionnaire probing their perceived control as well as their enjoyment and perceived success in the task using a continuous scale ranging from 1 (not at all) to 100 (very much).

If the effect's distance from the to-be-affected target directly modulates the effect of having an effect on action selection we would expect that reaction time would increase as the distance from the to-be affected target increases (Distant effect > Touching effect > Half-

[9] Notwithstanding the fact that theoretically (whether Bayesian informed or 'Comparator based') it is the *predictability* and not the sheer distance of an action's effect that should affect implicit measures of control (e.g., sensory attenuation) in many previous studies spatial (and temporal, as in our Exp.1a) contiguity was constant (Haggard et al., 2002). Theoretically, such high-precision cue should be *highly weighted/learned by the comparator* and hence quickly lead to 'normal' computation agency. The reported results do not support this pattern though. Thus, whether implicit measures of control are sensitive to efferent copy based-predictability per se or, rather the lack of fit with *the intention* is not yet established.

overlapping effect). In addition, if the effect of having an effect is modulated by the (spatial) predictability of the effect we would expect that reaction time would be shorter in the Distant effect condition than in the Random effect condition.

Results and Discussion

Performance: Reaction Time

Before analyzing the data we applied these filters in the following order: participants with more than 50% incorrect responses (three participants, ~2%), responses that were either above 700ms or below 200ms (5218/26640=~19%), incorrect trials (681/26640 = ~2%), and trials that deviated from their condition's mean by 2 or more standard deviations in either mean reaction time and percent correct (1293/26640=~4%). Responses failing these filters were removed and not analyzed further.

A oneway ANOVA with Effect (No effect vs. Overlapping effect vs. Random effect vs. Touching effect vs. Half overlapping vs. Distant effect) as a between-participants factor yielded a reliable effect of Effect ($F_{5,\,128}$=6.27, root *MSE*=56.92, p<.01). A planned contrast revealed that reaction time was shorter in the Overlapping (standard) condition (M=451.34, SD=46.32) than in the No-effect condition (M=486.76, SD=62.24) [$F_{1,\,128}$=4.35, p<.05, d=.64, CI_{95} (2, 68)] (Fig. 6). This finding again replicates the findings presented above and in previous studies (Karsh & Eitam, 2015a; Eitam et al., 2013) and provides additional support that 'having an effect' facilitates action selection

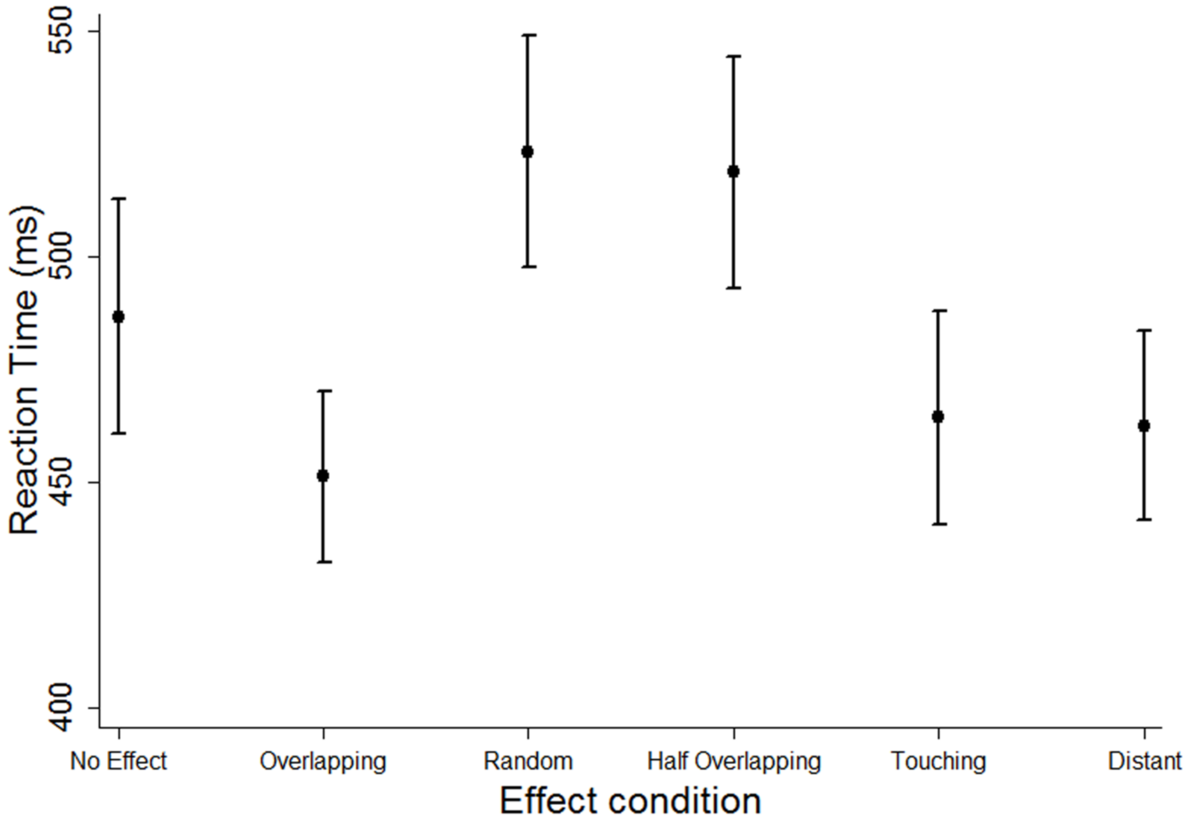

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Fig. 6. Experiment 2a: Mean reaction time by condition. Error bars depict 95% CI.

To test whether the effect's distance from the target affected the speed of action selection, we used orthogonal polynomial contrasts to test whether a linear trend of participants' reaction time as a function of the effect's distance from the target exists (using the Distant, Half Overlapping and Touching effect conditions). Note that all three conditions have identical (25%) predictability levels and only vary on the effect's distance from the to-be-affected target. As can be seen in Figure 6, a quadratic [$F_{1,67}$=13.9, p<.05, CI_{95} (-40, -12)] but not a linear trend [$F_{1,67}$=.01, p=.91, CI_{95} (-14, 13)] fits the results. As can be seen in Figure 6, this trend emerges from the longer RT in the Half Overlapping effect condition, which was not predicted. At the very least these findings weaken the possibility that it is the distance of the action-effect from the to-be-affected target per se is what affects the speed of action selection.

To test whether spatial predictability of action effects influences the speed of further action selection, we tested the contrast between the Random effect condition (in which the effect's location was also most unpredictable) and the Distant effect condition (in which the effects' location was less random as it could appear only in one of four locations). Reaction time was shorter in the Distant effect condition (M=462.68, SD=50.25) compared to the Random Effect (M=523.36, SD=57.23) condition [$F_{1, 128}$=11.59, p<.05, d=1.1, CI_{95} (-94, -26)]; but see caveat below.

These analyses grant some support to the conclusion that (spatial) predictability of action effects rather than their sheer distance from the to-be-affected target affected speed of action selection (i.e. modulated the effect of having an effect). However, beyond the anomalous result obtained in the half-overlapping condition -- randomness and distance were confounded in Experiment 2a; this is due to the fact that unwittingly the average distance from the target in the Random effect condition was also greater than in other conditions. Hence, this experiment does not firmly rule out the possibility that the slower reaction time in the Random effect condition did in fact emerge from the sheer distance of the delivered effect from the to be affected target. Experiment 2b was conducted to replicate the pattern while unconfounding distance and spatial precision of the effects.

Given our previous findings regarding the differential direct and indirect effects (through explicit judgments of agency) of control relevant factors on action selection, we also analyzed the effect of spatial predictability on participants' perceived control and its association with action selection.

Explicit Judgment of Agency

Beyond exploring the relationship between participants' perceived control and spatial predictability, we also tested whether perceived control affected participants' reaction time. Based on the control based response selection framework (Karsh & Eitam, 2015b) and previous work (Karsh & Eitam, 2015a), we expected that perceived control would not affect participants' reaction time (which is seemingly unaffected by explicit judgments of control).

First, we tested whether participants' perceived control was affected by having an effect. A two-tailed t-test confirmed that participants' perceived control was higher (albeit, marginal significant) in the Overlapping effect (standard) condition (M=56.68, SD=33.16) than in the No-Effect condition (M=40.34, SD=28.43) [t_{43} =1.77, SE=4.72, p=.08, d=.52, CI_{95} (-34, 2)]. In addition, participants' perceived control was not correlated with their reaction time (r=.02, p=.76).

As when analyzing participants’ reaction time, we used orthogonal polynomial contrasts to test whether there is a linear or quadratic trend in participants’ perceived control as a function of the effect’s distance from the target in the Distant, Half Overlapping and Touching effect conditions. In contrast to reaction time, there was a linear [$F_{1, 67}$=9.29, p<.05, CI_{95} (2, 14)] but not a quadratic trend [$F_{1, 67}$<.01, p=.97, CI_{95} (-5, 5)] between participants’ perceived control and the effect’s distance from the target. This pattern (which we did not predict and which should be treated with caution until replicated) suggests that participants felt more control as the effect’s distance from the target *increased*.

We also tested whether and how spatial predictability influenced perceived control. A planned contrast between the Overlapping effect (which was fully predictable) versus the Random effect, Touching effect, Half Overlapping effect and Distant effect conditions (which were less predictable) revealed that perceived control did not differ between the spatially fully predictable (and spatially contiguous) and the other less predictable effect conditions [*M*=56.57, *SD*=24.31; $F<1$, CI_{95} (-12, 12)].

This pattern of results is consistent with the hypothesis that spatial predictability directly affects the speed of response selection rather than affecting it through affecting explicit judgments of control.

Experiment 2b: Dissociating the Effects of Spatial Contiguity and Predictability on the Speed of Action Selection

Method

Participants

One hundred and twenty five students [104 females, Age (*M*=22.52, *SD*=3.51)] from the University of Haifa participated in the study in exchange for course credit or 20 Shekels (~$6).

Stimuli and Procedure

In Experiment 2b we used the same task as in Experiment 2a with a number of critical modifications (see, Fig. 7). The experiment included five conditions: an Overlapping effect (standard) condition; a No-effect (standard) condition; a Touching effect condition; a Distant effect condition and a Random effect condition in which the effect appeared at random locations that varied within a radius of 2.4 cm from the target.[10] As in Experiment 2a, in the Random effect condition the chance of predicting the location of the next effect was practically nil.

Crucially and unlike Experiment 2a, in this experiment the effect was *fully predicted* in the Touching and the Distant effect conditions (by holding constant its distance and angle relative to the to-be affected target circle). A second crucial modification was that the *maximal* distance of the effect from the target in the Random effect condition was set to equal the distance

[10] We did not include a half-overlapping condition in this experiment.

between the effect and the target in the Distant effect condition. This meant that the expectancy of the effect-target distance in the Random effect condition was now in fact *smaller* than that of the Distant effect condition.

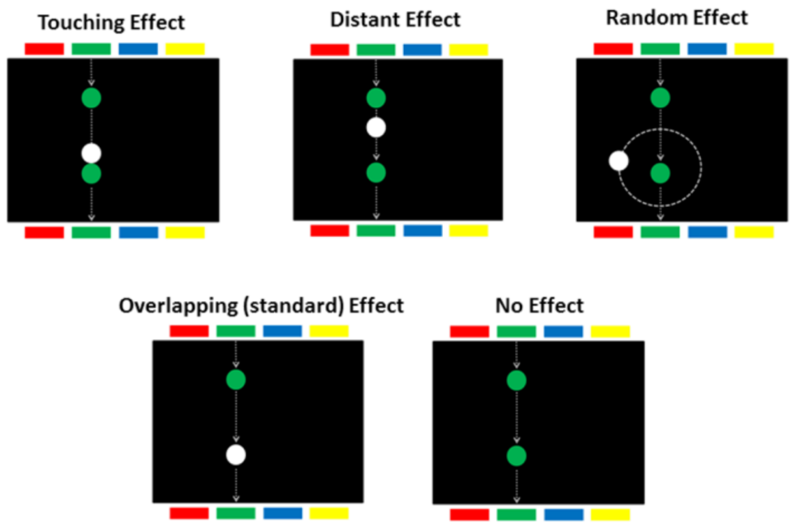

Fig.7. An illustration of the possible locations of the effect in each experimental condition. In the Overlapping effect (standard condition) the effect (white circle) overlapped the response cue (red circle) when a relevant response was made. In the No-effect condition, no effect appeared after a response. In the Touching effect condition, the effect "touched" the upper side of response cue. In the Distant effect condition, the effect appeared ~2.4cm above the response cue. In the Random effect condition, the effect could appear anywhere in a circle with a radius of ~2.4cm from the response cue. In the No-effect condition, no effect appeared after a response.

These two modifications enabled us to quantify the individual contributions of spatial predictability of the effect and its distance from the target on reaction time. The task was comprised of 10 practice and 180 experimental trials. After completing the task participants completed a computerized self-report questionnaire.

Results and Discussion

Before analyzing the data we applied the same filters used in all previous experiments. Participants with more than 50% incorrect responses (none), responses that were either above 700ms or below 200ms (1127/22500=~5%), incorrect responses (1367/22500 = ~5%) and trials that deviated from their condition's mean by 2 or more standard deviations in either mean reaction time and percent correct (1715/22500=~7%) were rejected from further analyses.

Performance: Reaction time

The pattern of results is clear-cut (Fig. 8). Beyond yet another replication of the shorter RT in the Overlapping effect (standard) condition (M=432.17, SD=45.84) compared to the No-Effect condition (M=459.42, SD=57.4) [t_{46}= 1.81, p<.05 one-tailed, d=.52, CI_{95} (-57, 2)], the Random location effect condition (M=448.54, SD=61.68) was slower compared to both the distant effect condition (M=420.55, SD=40.08) [t_{45}=1.85, p<.05 one-tailed, d=.53, CI_{95} (-2, 58)] and no different than the standard No- effect condition (t_{45}<1).

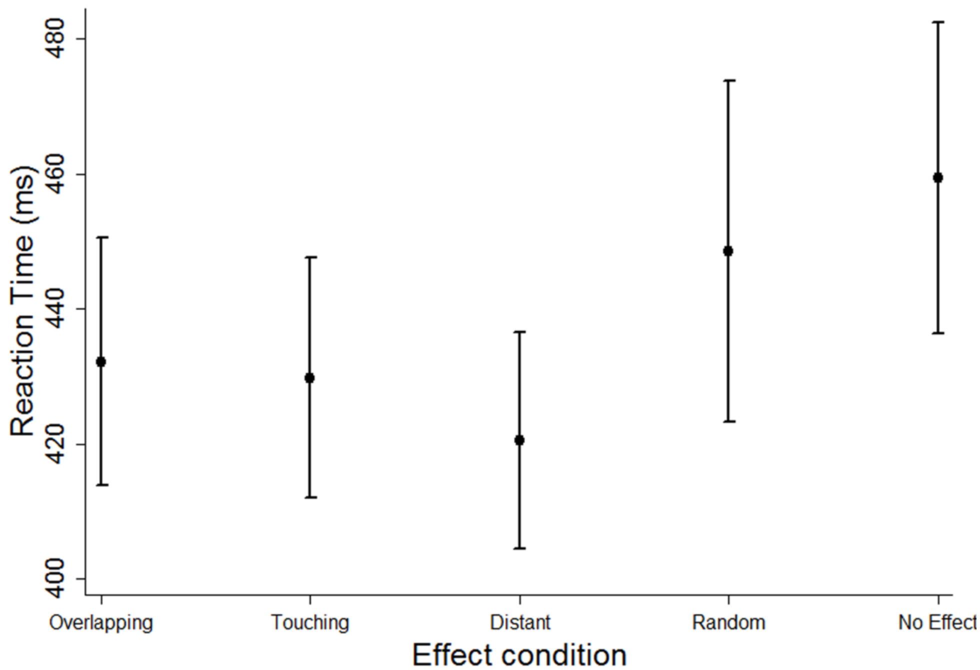

Fig. 8. Experiment 2b: Mean reaction time by condition. Error bars depict 95% CI.

To test whether the effect's distance from the target affected the speed of action selection, we used orthogonal polynomial contrasts to test whether there is a linear (or higher order) trend of participants' reaction time as a function of the effect's distance from the target in the Overlapping, Touching and Distant effect conditions; in all three conditions the spatial location of the effect was fully predictable and only the effect's distance from the to-be-affected target varied. As can be seen in Figure 7, there no such linear [$F_{1, 67}$=.88, p=.35, CI_{95} (-14, 5)] or quadratic [$F_{1, 67}$=.10, p=.75, CI_{95} (-12, 8)] trends emerged; suggesting no monotonic (or non-monotonic) influence of the effect's distance from the target on the speed of action selection.

These findings show that regardless of whether the distance of the effect from the target in the Distant effect condition was smaller (Experiment 2a) or larger (this experiment) than that of the Random effect condition's – the spatial precision of the effect modulated the effect of having an effect on response speed. Thus, it is the predictability or precision of the location of an action effect (and not the distance of the effect from the target cue) that facilitates the selection of the relevant response.

Explicit Judgment of Agency

As in the experiments above, we also measured participants' perceived control; as in Experiment 1b, we also probed for participants' causal attribution of the effects as being a consequence of their actions. This experiment also allowed us to test whether explicit judgments of control will show a similar (lack of) sensitivity to distance of the effect from the to-be-affected target and to its spatial precision; another possibility is that the influence of these factors on action selection and explicit judgment of control can be dissociated. Finally, given our previous results we predicted that perceived control would be unrelated to participants' reaction time (which we hypothesize as being insensitive to explicit control judgment).

First, we tested whether participants' perceived control was affected by having an effect. A one-tailed t-test between the Overlapping (standard) condition and the No-effect condition revealed that participants reported having numerically higher level of control in the Overlapping condition (M=50.45, SD=31.99) vs. the No-effect condition (M=38.95, SD=35.03) but this difference was not significant (M *difference*=11.5, t_{46}=1.18, p=.12, d=.34, CI_{95} (-4, 27)].[11] No other differences in perceived control were observed.

As for causal attribution of effects to their actions, a one-tailed t-test showed that participants reported higher levels in the Overlapping effect (M=74.25, SD=25.62), Distant effect (M=71.29, SD=25.06) and Touching effect (M=65.86, SD=28.89) conditions compared to the No

[11] A Bayesian analysis using a uniform prior distribution of possible effects ranging from 0-20 points gives a Bayes factor of ~1.6, suggesting that our data is insensitive so we don't make much of this finding (Dienes, 2014).

effect condition (*M*=52.33, *SD*=33.18) [(t_{46}=2.56, *p*<.05, *d*=.73, CI_{95} (4, 39)], [(t_{46}=2.23, *p*<.05, *d*=.64, CI_{95} (1, 36)] and [t_{46}=1.46, *p*=.07, *d*=.42, CI_{95} (-5, 32)], correspondingly.

As when analyzing participants' reaction time, we used orthogonal polynomial contrasts to test whether there is a linear trend of participants' causal attribution as a function of the effect's distance from the target in the Overlapping, Touching and Distant effect conditions. There was no linear [$F_{1, 67}$=.15, *p*=.70, CI_{95} (-7, 5)] nor quadratic trend [$F_{1, 67}$=1.01, *p*=.31, CI_{95} (-3, 9)] between participants' causal attributions and the effect's distance from the target.

Differing from perceived control though, participants also reported higher levels of self-causality in the Overlapping effect condition compared to the Random Effect condition (*M*=59.6, *SD*=30.76) [(t_{45}=1.77, *p*<.05, *d*=.51, CI_{95} (1, 31)], which did not differ from the No-effect condition (*M*=52.33, *SD*=33.18) [(t_{45}=0.77, *p*=.44, CI_{95} (-11, 26)]. This suggests that participants' causal attribution of the effects to their own actions is sensitive to the spatial predictability of action effect (but see Exp. 1b) – we return to this finding in the General Discussion. In addition, participants' reported perceived control and causal attributions were positively correlated to a medium degree (*r*=.43, *p*<.05), suggesting that while those measures entail some shared variance (~18%), they do not fully overlap—a point we return to in the next section (see also Frith, 2013). Importantly, neither perceived control (*r*=.16, *p*=.08) nor causality (*r*=.03, *p*=.71) correlated with reaction time.

To conclude, the findings of Experiment 2b show that only spatially predictable (rather than spatially contiguous) action-effects facilitate action selection. Although there was an indication that some explicit judgments of control (i.e. self-causality) is also sensitive to spatial precision the effect of spatial precision on action selection do not seem to be mediated by such explicit judgments. In passing, the findings also suggest that different explicit measures of the sense of agency may vary in their sensitivity to different control parameters. As mentioned above and regardless of this differential sensitivity, neither explicit measure was correlated with the speed of action selection.

To directly test whether the absent of significant correlation between participants' reaction time and perceived control supports the null hypothesis, we performed a Bayesian calculation of the correlation between participants' mean reaction time and their perceived control in both effect and no-effect conditions (Exp.1a, Exp.2a and Exp. 2b collapsed) using JASP software (Love et al., 2015). The resulting Bayes Factor of .09 lends strong support for the Null which is that there exists no correlation between the two measures and to the notion that reaction time reflects a consciously unavailable stage of response selection that is unaffected by explicit judgments of control.

General Discussion

The principle goal of the current research was to test whether the motivational impact of 'having an effect' is modulated by factors previously shown to influence the sense of agency. We hypothesized that temporal and spatial contiguity\predictability as established objective control-relevant information for one's motor-based computation of agency, will modulate how 'having an effect' impacts further response selection. The experiments provide substantial support that this is indeed the case, implying that the (motivating) effects on behavior are driven by agency-relevant information.

Implications For the Control-based Response Selection Framework

The findings of the current research provide empirical support for the control-based response selection framework (Karsh & Eitam, 2015b). Specifically, consistent with this framework, factors previously shown to affect so called ‘implicit markers of agency’ (e.g., temporal contiguity between actions and effects) were found to facilitate the speed of responding (presumably, indexing influence on the stages of response selection that are consciously unavailable, e.g., the selection of movement parameters). Importantly, as predicted by the framework, these effects are seemingly ‘direct’ in the sense of being independent of explicit control knowledge or judgments (lower part of Route B in Figure 1). In addition, and also consistent with the control-based response selection framework, such factors (temporal contiguity; Exp.1c) were also found to influence ‘higher’ (and potentially consciously accessible) stages of response selection (indexed by changing response frequency which is assumed to reflect influence on the effector selection). This influence also occurred independent of explicit control knowledge and judgment (upper part of Route B in Figure 1).

Although exploratory, it seems that control relevant information differs in its salience to the conscious observer. Specifically, while a previous study (Karsh & Eitam, 2015a) showed higher levels of explicit knowledge of action-effect contingency (the probabilities of receiving effects to the different keys), participants accumulated less explicit knowledge about the temporal contiguity between actions and effects (see Table S1 and Footnote 5). This (apparent) differential sensitivity enabled us to see the dissociation between the direct and indirect influences of control relevant information on response frequency [Please refer to Figure 9, for a graphic summary of the empirically established direct and indirect influence objective factors have on reaction time and response frequency.]

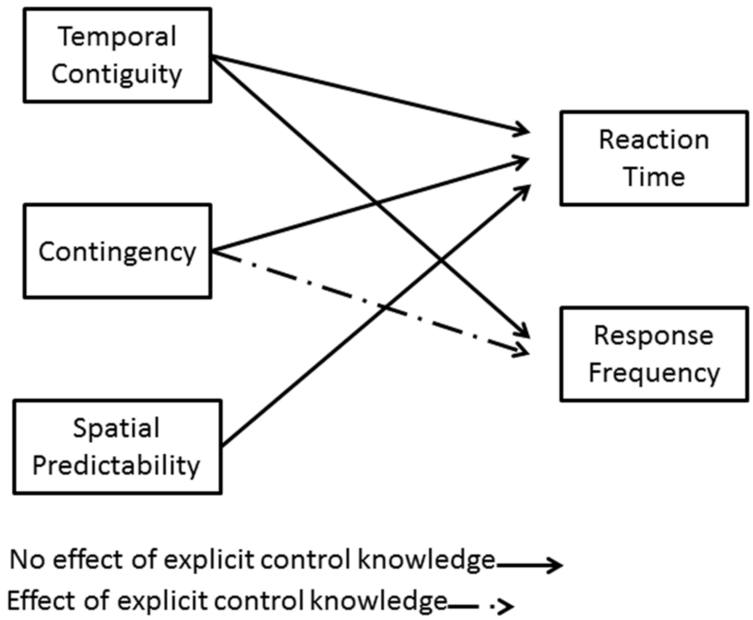

Fig.9. A visual summary of the direct and indirect influences control relevant factors have on reaction time and response frequency based on findings from both the current study and from Karsh and Eitam (2015a).

Differential Sensitivity of Explicit Judgments of Agency to 'Control-Relevant' Factors?

Examining whether and when temporal contiguity and spatial predictability (or contiguity) affect explicit judgments of agency, we used a number of differently worded probes that were used by different researchers to measure explicit judgments of agency: 1. Perceived control (Exp.1 and Exp.2), a similar ('metacognitive') item to the one used by Metcalfe & Green, (2007), 2. Temporal contiguity awareness (Exp.1c), similar to the one used by Karsh and Eitam, 2015a) and 3. Causal attribution of an effect to one's own previous action (Exp.1b and Exp.2b; Chambon & Haggard, 2012; Sato, 2009; Sato & Yasuda, 2005; Gentsch, Kathmann & Schutz-Bosbach, 2012).

First, our most stable finding is that perceived control (across item wording) is primarily affected by merely having an effect regardless of the effect's temporal contiguity or spatial predictability. This may reflect participants' lay theories about what are 'effects' in this context, and/or what ‘effects’ the experimenters are referring to. In any case, the relation between these judgments and our behavioral indices are consistent with Karsh and Eitam (2015a) in that perceived control per se (differing from what we termed above ‘control relevant factors’) was not reliably related to the speed of action selection. Second, in contrast to perceived control, participants’ causal attribution of effects to their actions (Exp. 2b) was *influenced* by the spatial predictability or precision of an action’s effect (but wasn’t correlated with speed of action selection).

Given the rising prominence of Bayesian inspired models that emphasize weighting of cues by their precision (see recent relevant reviews by Rowe & Wolpe, 2015; Gentsch & Schütz-Bosbach, 2015), clearly more work is required to determine when/whether this principle plays a different role for (different) explicit judgments of control, and as a direct effect on action selection. Third, because Experiment 1c included different temporal lags for each key for each participant, it was possible to measure participants’ awareness of the temporal contiguity between actions and effects. As described in the Introduction, participants’ action-effect contingency knowledge was predicted to affect ‘high level’ response selection (e.g., which finger to respond with). It seems that in the case of temporal contiguity, the poorness of explicit knowledge of the temporal contiguity mapping led to its lack of influence on such high level selection (Experiment 1c).

To conclude, whether explicit judgments of agency are affected by temporal contiguity and by spatial predictability may depend on (1) the specific question about agency that participants are asked (e.g., control over one’s action *vs*. control over the effect of one’s action, see also Pacherie, 2008; Rotter, 1954), (2) the salience of the contingencies and (3) the level the of temporal asynchrony of the effect to the action to the conscious observer (Ma & Hommel,

2015) and (4) possibly, by people's beliefs about the nature of the mechanism mediating actions and effects (e.g., a key press versus ringing the doorbell). More surprisingly, the direct and indirect effects of control relevant factors are asymmetric in more than one way. Based on both the current and previous (Karsh & Eitam, 2015a) findings, we claim that objective control-relevant information may influence high-level action selection *only* when no explicit knowledge of control is available.

Finally, it is important to stress again that regardless of wording, in all five experiments reported in our research, explicit control judgments were *not* found to correlate with a stage of action selection that is considered to be consciously inaccessible (here, indexed by reaction time).

To note, one limitation of the study is the potential differential sensitivity of reaction time (measured trial-by-trial) and explicit control judgment (measured only at the end of the experiment). However, differing from the case of perceived control, it is expected that people's reports of *explicit knowledge* should be maximal after a substantial degree of exposure (e.g., to the pairing of action and effect); hence a single measurement at the end of the study (rather than, for example, averaging across multiple measurements throughout the study) is possibly the most valid measure for evaluating people's accumulative knowledge.

Can an Internal Prediction Model Explain How Temporal Contiguity and Spatial Predictability Between Actions and Effects Impact the Speed of Response Selection?

Previous work testing the effect of spatial contiguity on sensory attenuation may have confounded spatial predictability with spatial contiguity (e.g., Blakemore et al., 1999). In the current study we found that it was spatial *predictability* or precision (as the inverse of variance of the spatial location of effects) that influenced the speed of action selection rather than the actual effect's distance from the to-be affected target per se. Based on the result from the current study and the explanatory framework of the 'comparator model' through which the sensory attenuation is predicted, we would expect that spatial predictability and not the spatial distance of the effect from the target would influence sensory attenuation. Given the above, future work should experimentally control the two factors to test their distinct effect on sensory attenuation. This hints to a potential dissociation between the temporal and spatial dimensions given that, apparently, reducing temporal contiguity *itself* diminished the impact of effects on action selection (as the lagged effects were fully predictable on all dimensions).[12]

While our findings (Exp. 2) regarding the effect of spatial predictability on action selection can be accommodated by a forward prediction model, it is less clear whether such a model can explain the influence of temporal contiguity. Specifically, we found that the impact of temporal contiguity on reaction time is stable over more than one hundred trials (see Fig. 2). Regarding another implicit measure of agency, Haggard, Clark and Kalogeras (2002) showed, using fixed blocks of different delays between action and effects, that delaying action effects by 450ms decreased the temporal binding effect even when the timing of the effects could be perfectly predicted. This finding fits well with the pattern of findings of Experiment 1a in which even after more than a hundred trials, there was no indication for calibration of the forward model in the form of decreasing the benefit of the immediate effects (compared to the lagged).

[12] The proposal that the temporal and spatial dimensions should have the same effects may seem to some readers as comparing apples and oranges. Within the literature on the sense of agency, however, it has been frequently argued that these two factors influence the same process (for a recent review see Haggard & Eitam, 2015).

This pattern raises the possibility that close temporal contiguity is a *fixed* parameter for judging control through the motor system; such as, "events that occur immediately + 100ms are effects". It is fixed in the sense that it is independent from the *content* of the sensory prediction and hence is 'resilient' to learning. This speculation is consistent with the notion that the motor control system must also be sensitive to novel (and hence unpredicted by the forward model) self-caused changes in the environment (Karsh & Eitam, 2015b; Redgrave & Gurney, 2006; Redgrave, Gurney & Reynolds, 2008). In such a case, the contribution of the motor system is in supplying the information that a motor program (or response) was activated and the timing of its activation (or enactment; Redgrave & Gurney, 2006; Redgrave, Gurney & Reynolds, 2008).

However, a different explanation could also accommodate this pattern. During our daily life experience, most of our control feedback is temporally *immediate* and spatially *constant*. This frequent experience could have created a very strong prior that overshadows incidental or minor deviations (see also Cravo, Haddad, Claessens & Baldo, 2013). If true, this does not necessarily weaken sensory prediction as an explanatory mechanism but it does suggest that it is far less calibrated for relatively transient environmental changes.

Yet another potential explanation for the stable sensitivity to effects' lag is grounded in different expected distributions for estimations of temporally short versus long durations. It is likely that estimating larger (*vs.* smaller) quantities would have more variance, and thus they would be less precise when the effect is delayed versus immediate or even very briefly lagged (200ms). Given this, the internal confidence in one's temporal prediction should be higher for immediate versus long delays. One can further speculate that the level of precision of a feature of the internal prediction model (e.g., time-to-effect) may positively influence the weighting of that cue and hence its effect on the speed of response selection. Obviously, more research is needed to understand whether the seemingly constant sensitivity of so-called implicit measures of agency to temporal contiguity is a fixed parameter or, instead, is also an e of an internal temporal prediction model and its precision.

The Ideomotor Theory and the Control-based Response Selection Framework

It is important to consider the commonality and the distinction between the control-based response selection framework tested here and ideomotor thinking (for recent review, see Shin, Proctor & Capaldi, 2010), especially in its influential version known as the theory of event coding (TEC; Hommel, Musseler, Aschersleben, and Prinz, 2001). Among other things, TEC aims to explain the transition between the acquisition of action effect knowledge and intentional action control (Elsner & Hommel, 2004).

In brief, TEC suggests a common representational system for perception (action effects) and action codes. Before any action effect knowledge is acquired, movements are selected in a seemingly random fashion (i.e., in newborns). The effect that co-occurs with the movement is somehow associated with the movement that was carried-out, such that (eventually) activating the code of a particular effect will 'automatically' activate the code of the particular action. According to TEC this bi-directional association is key to becoming a goal-directed agent.

The control-based response selection framework is strongly influenced by current neuro-cognitive models of action selection that highlight the role of the neurotransmitter dopamine in the selection of optimal actions. It is important to note that the control-based response selection framework does not diminish the role of ideomotor theory in action selection. Instead, it compliments it by explaining how (and when) – in lieu of goals – control-relevant information affects the acquisition of action-effect associations, and how this contributes to further response selection at different levels of abstraction. In fact, our proposed framework nicely compliments the TEC, which is silent regarding the mechanism that leads to the creation of 'events'. The control-based response selection framework addresses this lacuna by suggesting that the brain's reward system drives action-effect association when these "obey" the parameters by which the mind decides that a perceptual event is an effect of its action.

By describing how these factors directly and indirectly influence different levels of response selection (e.g., the selection of movement parameters versus the selection of the effector), the control-based response selection framework drives predictions that cannot be accounted by the TEC. For instance, TEC argues that perceptual ('effects') and motor codes are bound into events. Hence, if an effect is associated with multiple motor codes, it should actually hamper action selection because it creates conflict by activating multiple motor codes. The results of Experiment 1b, where an identical perceptual effect (in location, color and shape) followed each one of the four relevant responses, show that this is not the case. As predicted by the control-based response selection framework, identifying own action effects is valuable to the organism and accordingly is 'marked' by reward. Selection of responses/motor parameters associated with reward then facilitates response selection.

As our research shows, this reward is contingent on the perceptual events being deemed as own-action effects rather than being passively stimulated by perceptual features of the effect that are (somehow) encoded with the action. Consider the case for the 'pre-conceptual' selection of motor parameters (indexed in the current study by participants' RT) that is inaccessible to conscious awareness and is insensitive to explicit control judgment. While each relevant effector (finger) in the immediate condition (Exp.1b) delivers an identical action effect, and hence no effector is more control-effective than the other; the selection of motor parameters (a process which includes far more degrees of freedom) will tend to converge for optimal (control-effective) motor parameters. This is because optimal motor parameters are ones that increasingly guarantee a shorter lag (hence more control-based reward) between the generation of a motor command and the registration of the effect.

Finally, an important difference between the methodological approaches should be noted. For instance, in Elsner and Hommel's (2004) study (Exp.1), participants performed an action-effect learning phase in which a discrete auditory effect appeared after each one of the four relevant responses. The temporal contiguity of the effect was manipulated (50ms, 1000ms and 2000ms). Following the learning phase, participants performed a test phase in which the effect appeared as an imperative stimulus. Very similar to what we tend to find in the motivation from control tasks, in the learning phase of Elsner and Hommel's experiment, there was a trend towards shorter RT in the 50ms (briefly lagged effect) compared to the other longer lag conditions; interestingly, the effect size was also very similar (30-40ms) to what we tend to find in our tasks (see also Eitam et al., 2013). This effect was not statistically significant possibly due to low experimental power given eight participants per group. Differing from the tasks used in the current study, Elsner and Hommel did not present participants with action-effects in the test phase. As such, the results there are not relevant to what we called motivation from 'having an own action effect'. Thus, although we think that the suggested-control based response selection framework is highly relevant for action-effect learning; it currently enables predictions only situations in which actions have (appropriate) effects.

Summary

Inspired by the Control-based response selection framework (Karsh & Eitam, 2015b), the current research investigated the direct and indirect effects of objective factors (e.g., temporal and spatial contiguity\predictability) on different stages of action selection. Consistent with the framework, we conclude that the information that is relevant for motor-based computation of agency modulates the motivating impact of ‘having an effect’, potentially by determining whether or not a perceptual event is an effect of one’s own actions and hence rewarded (by control). The current research brings important empirical support to the control-based response selection framework (Karsh & Eitam, 2015b) by showing the conditions and the processes of by which ‘having an effect’ becomes motivating control feedback.

The current research points to exciting new theoretical and applied possibilities. On a theoretical level, our findings are another step in establishing that a new category of events (own action effects) should activate the brain’s reward system (cf. Redgrave et al., 2008). As suggested above, our framework outlines the mechanism for how the minds ‘bootstraps’ random own-action effects to generate a behavioral repertoire for objective agency. On a practical level, it suggests that various phenomena – from habits to conditions such as ADHD, may involve imbalances in the reward value or the registration of own action effects.

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Author Contributions

N. Karsh and B. Eitam developed the study concept. N. Karsh, I. Mark and B, Eitam designed the study. N. Karsh collected the data. N. Karsh and B. Eitam performed the data analysis and its interpretation. N. Karsh, I. Mark, B. Eitam and E. T. Higgins wrote the paper. All authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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