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**Self-Reference in Action: Arm-Movement Responses Are Enhanced in Perceptual  
Matching**

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## **Abstract**

Considerable evidence now shows that making a reference to the self in a task modulates attention, perception, memory, and decision-making. Furthermore, the self-reference effect (SRE) cannot be reduced to domain-general factors (e.g., reward value) and is supported by distinct neural circuitry. However, it remains unknown whether self-associations modulate response execution as well. This was tested in the present study. Participants carried out a perceptual-matching task, and movement time (MT) was measured separately from reaction-time (RT; drawing on methodology from the literature on intelligence). A response box recorded 'home'-button-releases (measuring RT from stimulus onset); and a target-key positioned 14cm from the response box recorded MT (from 'home'-button-release to target-key depression). MTs of responses to self- as compared with other-person-associated stimuli were faster (with a higher proportion correct for self-related responses). We present a novel demonstration that the SRE can modulate the execution of rapid-aiming arm-movement responses. Implications of the findings are discussed, along with suggestions to guide and inspire future work in investigating *how* the SRE influences action.

**[Key words: self-reference effect, self-prioritization, movement time, rapid arm movements, visuomotor processing]**

## 1. Introduction

An extensive literature now demonstrates the Self-Reference Effect (SRE): that is, performance is faster and/or more accurate across attentional, perceptual, decision-making, and memory-based tasks when stimuli are associated with the ‘self’ as opposed to (e.g.) another person or a neutral item (Conway & Pleydell-Pearce, 2000; Humphreys & Sui, 2015; Schäfer, Wentura, & Frings, 2017; Sui & Humphreys, 2015; Symonds & Johnson, 1997; for a review see Cunningham & Turk, 2017). Studies using a socio-associative perceptual-matching paradigm (Sui, He, & Humphreys; 2012), have further shown that the SRE is independent of stimulus familiarity, cannot be reduced to domain-general factors (e.g., inherent reward value, positive emotional valence, or semantic elaboration; see Humphreys & Sui, 2015; Sui & Humphreys, 2015), utilises domain-specific information (Sun, Fuentes, Humphreys, & Sui, 2016), and is supported by distinct neural circuitry (Sui, Rotshtein, & Humphreys, 2013b).

To date, studies using Sui and colleagues’ matching paradigm to investigate the SRE have typically focused on early and perceptual processing. The SRE has been shown, for example, to modulate access to visual awareness (Visokomogilski, Golubickis, Cunningham, & Sahraie, 2017), and attention (Sui, Liu, Wang, & Han, 2009; Golubickis et al., 2017). The SRE has also been demonstrated when the paradigm has been transferred to audition and touch (Schäfer, Wesslein, Spence, Wentura, & Frings, 2016). Few studies, however, have examined the influence of the SRE on later processing (cf. Constable, Welsh, Huffman, & Pratt, 2018; Siebold, Weaver, Donk, & van Zoest, 2015; Stein, Siebold, & van Zoest, 2016), and none have directly examined effects on response execution.

Frings and Wentura (2014) examined the effects of self-prioritization and an action variable in Sui et al.’s (2012) paradigm. The authors instructed participants to associate labels

with arm movements, and then (cued by a directional cursor) to execute these movements in the matching task. A label was then presented after the arm-action had terminated, and participants had to judge using button-presses whether the movement and label matched. The authors documented a reaction-time (RT) advantage in matching the ‘self’ label to its corresponding arm movement. As Schäfer, Wentura, and Frings (2015) note, these findings revealed a performance advantage in matching the ‘self’ label with an ‘action representation’. Response execution itself was not directly measured.

Recently, Macrae, Visokomogilski, Golubickis, Cunningham, and Sahraie (2017) reported a study designed to assess the influence of the SRE on access to visual awareness. Using a hierarchical-diffusion-model analysis, and in contrast to Frings and Wentura (2014), the authors decomposed task performance on Sui et al.’s (2012) paradigm. It was found that the SRE influenced both decisional as well as non-decisional processes. However, since non-decisional processes can include one or both of stimulus encoding and response execution, it remains unclear whether response execution can be modulated by self-associations.

Currently, there is no theoretical model available which explicitly links mechanisms of self-reference with response execution processes. Mechanistic understanding of the SRE is still in its infancy, and focus has so far been on processes in perception and attention (see e.g., Humphreys & Sui, 2016). In contrast, however, the mechanisms underlying response priming (RP) – a paradigm that has been used extensively to explore visuomotor processing [or early and perceptual processing effects on response generation] – have been well-documented (Schmidt, Haberkamp, & Schmidt, 2011).

‘Rapid chase theory’ (Schmidt, Niehaus, & Nagel, 2006) posits two components of visuomotor processing: an initial bottom-up, feed-forward activation of the visual system in stimulus processing which leads to rapid and direct motor activation, and which is

independent of visual awareness. This is contrasted with a slower, top-down-controlled, ‘recurrent processing’ component, arising in later processing, that feeds back to influence re-entrant activity, as well as developing visual awareness (Schmidt & Seydell, 2008). The SRE has been proposed to modulate both bottom-up processes and top-down attentional control mechanisms, and also to operate outside of visual awareness (Macrae et al., 2017; Visokomogilski et al., 2017; although cf. Constable et al., 2018; Stein et al., 2016).

Researchers in RP have been able to dissociate effects of the two modes of visual processing on response execution, by varying task parameters in terms of the SOA of the ‘prime’ (a stimulus presented below the threshold of awareness) and target stimuli (available to conscious perception), and their response compatibility and incompatibility mappings (see e.g., Schmidt et al., 2011). In particular, a variant of RP (which investigates the time-course of primed pointing movements) has enabled researchers to dissociate early pre-conscious versus late processing effects on visual motor control: The initial “feed-forward sweep” triggered by the prime stimulus (Schmidt et al., 2006) has been shown to drive early parts of the movement (or, under certain conditions, even the whole response – e.g. generating overt errors on stimulus-response incompatibility trials)<sup>1</sup>. The slower (top-down) target-stimulus processing can then take over movement control mid-flight (with this time-point tightly-linked to the SOA), and further influence response execution ‘online’ as it unfolds (Schmidt & Seydell, 2008; Schmidt et al., 2011). The SRE, then, could operate within either or both of these modes of visual processing and exert an influence response execution.

As well as potentially interacting with established modes of processing, an SRE in action may involve processes that are qualitatively distinct. The SRE has been shown to be

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<sup>1</sup> Prime information typically drives the errors in inconsistent conditions and can lead to a full-blown response error (Schmidt et al., 2011).

supported by distinct neural circuitry (Sui et al., 2013b). In particular, imaging work (Sui et al., 2013b) has revealed that the SRE arises from a functional coupling of the ventral medial prefrontal cortex (vmPFC) – an area associated with self-representation – and the left posterior superior temporal sulcus (lpSTS; the ventral attentional network linked to social attention). In contrast, other-person-related responses on the same task activated the dorsal frontoparietal attentional control network. In a recently proposed processing network – the Self-Attention Network [SAN] model [Humphreys & Sui, 2016] – (which has yet to be integrated into the processing frameworks so far understood in RP), self-associated stimuli are held to rapidly activate a self-representation located in the vmPFC, which then primes responses in the pSTS and enhances bottom-up driven (orienting) processing of self-related stimuli. Top-down (fronto-parietal) attentional control (associated with the intra parietal sulcus; IPS) can enhance self-related responses by engaging with prior expectancies for self-stimuli, but also inhibit bottom-up-driven self-related responding for other-person-related responses (Humphreys & Sui, 2016). The involvement of distinct self-related circuitry, then, could support visuomotor processing effects that are qualitatively distinct from those previously found in the case of RP. There may also be overlap, however, through the interaction with top-down and bottom-up mechanisms.

In terms of the slower, top-down, later (recurrent) and online processing outlined in RP, there is some suggestion that the SRE could influence response execution via this route. In the SRE literature, it has been shown that not only can the SRE be enhanced by increasing expectancies for self-stimuli, but that these expectancies dominate performance over those for other-person-related stimuli (Sui, Sun, Peng, & Humphreys, 2014). RP theory holds that when stimuli match expectations regarding stimuli and their assigned responses, the corresponding motor response is triggered directly (Kiesel, Kunde, & Hoffman, 2007). In

terms of online control (Khan et al., 2006), it has been found in ownership paradigms, for example, that perceived social context can modulate the kinematics of unspeeded (non-rapid) reach-and-grasp actions. Constable, Kritikos, Lipp, and Bayliss (2014) found that participants' reaches to their own rather than the experimenter's mug were straighter; in contrast, reaches to the experimenter's mug exhibited a curved trajectory. However, these studies were designed to investigate a different construct ('ownership' – see Constable et al., 2018) and type of action (unspeeded reach-and-grasp) from the current study (and evidence is equivocal, for example, that a perceptual SRE remains intact in these paradigms; Constable et al., 2018).

In terms of bottom-up processing, RP research indicates that visual attention can intensify the first waves of bottom-up visuomotor processing (Schmidt & Seydell, 2008). Heightened stimulus energy (e.g., in stimulus contrast) has been shown to produce increased feed-forward activity which builds activation more rapidly in cortical motor areas linked to movement execution (and shortens response times; Schmidt, Niehaus, & Nagel, 2006). Similarly, higher-intensity stimuli increase activation to the response stage, which increases response force (Ulrich, Rinckenauer, & Miller, 1998). If the vmPFC 'primes' attentional responses in the pSTS to self-stimuli (Humphreys & Sui, 2016), the SRE could potentially influence response execution via e.g. a saliency-akin-driven mechanism. Indeed, effects of self-reference have been compared to those of highly perceptually-salient stimuli. Responses are faster and more accurate, reduced stimulus contrast does not affect the SRE (Sui et al., 2012), and the bias is arguably somewhat automatic (Alexopoulos, Muller, Ric, & Marendaz, 2012; Humphreys & Sui, 2015; Sui et al., 2014; although cf. Ocampo & Kahan, 2016). Furthermore, in a level-priming paradigm, both perceptual saliency and self-reference were



shown to modulate target selection in hierarchical stimuli (Liu & Sui, 2016) and both modulate attentional suppression mechanisms that recruited the IPS (Sui, Liu, Mevorach, & Humphreys, 2013a).

The SRE is not simply a general saliency-driven effect, however. For example, the effects of the semantic distinctiveness of stimuli can be dissociated from the SRE (Schäfer, et al., 2017), and when stimuli are both socially- and highly-perceptually-salient, response accuracy is increased relative to the effects of simply perceptually-salient stimuli (Liu & Sui, 2016). Furthermore, perceptual and ‘social salience’ (a term coined by Sui and colleagues [2013a] to describe effects of self-reference on early processing) also activate distinct neural areas (Sui et al., 2013a). Effects of perceptual saliency are thought to originate from early visual areas. In contrast, those of ‘social saliency’ are thought to be generated in the vmPFC (Liu & Sui, 2016). Therefore, as noted, the SRE may be able to influence one or both of the modes of visuomotor processing (identified in RP). However, the recruitment of a dedicated ‘self-network’ may result in qualitatively-different visuomotor processing than has so far been identified in RP.

In attempting to predict effects of self-reference on response execution, there is also the consideration that effects established at the perceptual level (potentially including the SRE) may not necessarily exert a corresponding influence on response execution processes. For, example in a recent study (Moher, Anderson, & Song, 2015), the authors found that increasing the saliency of distractors during goal-directed action enhanced the efficiency of responses, which is in stark contrast to effects in perceptual processing. They suggest that high-saliency in fact suppresses action-related interference. Self-reference could potentially

exert no influence, or extinguish, or reverse the sign of its perceptual effects in response execution.

Turning now to the motor control and neuroscience literature, three key components of motor processing have been identified which stand as potential candidates for modulation by the SRE. These are: movement preparation (Khan et al., 2006), a movement initiation signal (Haith, Pakpoor, & Krakauer, 2016; see also Weinberg, 2016), and online action-control (Khan et al., 2006). It is generally accepted that the planning and online control of movement are distinct processes (e.g. Glover, 2004; and see Khan et al., 2006). However, until recently, it was thought that movement initiation (response release) and preparation were yoked (the former triggered on completion of the latter) and that RT therefore reflected preparation time (Haith et al., 2016). Recent work in the neuroscience literature has indicated that, on the contrary, the mechanisms underlying response release and preparation time may be independent (Haith et al., 2016). On this view, instead of preparation time, it is the movement initiation signal that determines RT. Response release can be delayed post preparation, resulting in longer-than-necessary RTs for achieving accurate responses on speeded tasks (see Haith et al., 2016). Conversely, response release can be brought forward and the movement commence before preparation is fully complete (e.g., resulting in increased error rates; see Haith et al., 2016).

In a re-working of Haith and colleagues' model, Weinberg (2016) proposes a modification entailing that the levels of the two signals (initiation/urgency and preparation) instead combine to determine RT (drawing on Cisek, Puskas, & El Murr's, 2009, urgency-gating evidence-accumulator model). This modification can account for the well-established finding that when decisions are more difficult, RT increases (necessitating specification of some form of temporal link between response release and preparation). When response

preparation activity takes longer to build up (Weinberg, 2016), this delays the release of the response (by taking longer to reach the release threshold). Furthermore, in a complementary finding, the urgency signal (which arises in the basal ganglia and drives commitment to the movement once chosen, but not response selection) has been found to regulate the vigor [speed and size] of movements (Thura et al., 2014; Thura & Cisek, 2017). Therefore, influence of the SRE on response execution could operate through preparation, online control, and also the urgency signal. Much future work is needed to unpick and systematically test the possibilities for *how* the SRE could influence movement execution. However, the important question of *whether* the SRE can modulate response execution must first be addressed. This is the aim of the current study.

Using a simple behavioural set-up, the current study examined the influence of the SRE on the movement time (MT) of (forward-motion) arm-movement responses in Sui and colleagues' (2012) matching task. Following the authors' procedure, we instructed participants to associate 'self' and 'stranger' labels with arbitrarily-assigned geometric shapes (e.g., you=square, stranger=circle). Participants then judged, in a speeded perceptual-matching task, whether the shape-label pairings, presented, matched the learned associations, or whether they had been swapped instead (e.g., self-circle, stranger-square). In a departure from Sui et al.'s total-response-time measure, we introduced a lesser known, but half-century-old, procedure drawn from chronometric studies of intelligence (e.g., Houlihan, Campbell, & Stelmack 1994; Jenson & Munro, 1979; also found in other literatures; e.g. Praamstra, Loing, & de Lange, 2014). Response time was divided into: (i) RT, measured from stimulus onset to release of a 'home' button, and (ii) movement time (MT) measured

from this release to the depression of a target key, situated 14cm from the release button. This permitted separate measurement of RT and MT.<sup>2</sup>

Firstly, if our motor-variant of the matching paradigm is robust, it would be expected that RTs for self- as opposed to stranger-matching responses would be faster, and therefore replicate findings of previous studies (e.g. Sui et al., 2012). Once this is established (via observation of an SRE in RT), it can be assessed whether the SRE can influence the three potential motor mechanisms: preparation of the response (influencing quality [accuracy] of the movement; Haith et al., 2016); the movement initiation/urgency signal<sup>3</sup> (linked to movement vigor – speed and size; Thura et al., 2014); and online action-control (influencing targeting-accuracy, and also speed via optimal trajectory corrections). It has already been established that response-release occurs earlier for self-related responses than for stranger-related responses (indexed by faster RTs; and we will assume here that our motor-variant is robust). Therefore, to determine whether the SRE affected either one or both of preparation and online action-control, we need only to rule out that the initiation/urgency signal alone was modulated. In this vein, we consider just the following: If the preparatory activity and online control across self- and stranger-related responses is held constant (preparation builds at an equal rate, and trajectories are equal), but self-related responses are released earlier due to an increased urgency/initiation signal (Haith et al., 2016; Weinberg, 2016), there are two

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<sup>2</sup> In previous studies investigating the SRE (e.g. Sui et al., 2012), button presses were used to measure total response time. Therefore, response initiation processes (henceforth referred to as RT-interval processes) and response execution processes were not isolated and measured separately.

<sup>3</sup> The response initiation (urgency) signal (i.e. identified by Haith et al., 2016) should be distinguished from “response initiation” (indexed by RT). To avoid confusion, we borrow from Maslovat, Klapp, Jagacinski, & Franks (2014) in referring to processes of the response initiation phase as “RT-interval processes” – these occur in the interval between stimulus onset and the release of the home button. The interval duration (RT) is determined by both the initiation signal and response preparation components (see Weinberg, 2016; although cf. Haith et al., 2016). In line with Weinberg (2016), we refer to the mechanism determining the time-point at which initiation of the response ends as a “response release” mechanism.

possibilities: (1) If release occurs before preparation has been fully completed (Haith et al., 2016), then we would expect to see faster MTs for the self-match condition<sup>4</sup>, but a lower proportion of correctly-completed responses as compared with the stranger-match condition. (2) If the release point for self-responses occurs after the preparation is complete (and stranger-related response-release occurs later relative to self-related response initiation due to a more weakly building urgency/initiation signal), then we would expect to see faster MTs for self-related responses, but an equal proportion of correctly-completed responses across self- and stranger-match conditions. Therefore, if faster MTs and a higher proportion of correctly-executed responses for the self-match condition are observed, we can conclude that response execution processes (i.e. one or both of response preparation and online action-control) were modulated by the SRE.

## 2. Methods

### 2.1 Participants

Thirty-five right-handed participants with normal or corrected-to-normal vision took part<sup>5</sup>. Five participants were excluded from data analysis – one participant completed only one session, two were multivariate outliers, and two performed at chance level (less than 55% accuracy). Data from thirty participants (11 male; age range 19–34 years; mean age and standard deviation,  $23.30 \pm 3.72$ ) were used in the final analysis. All participants completed a written consent form approved by the Oxford Research Ethics Committee (MSD-IDREC-C1-2013-209 and R49190/RE001).

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<sup>4</sup> Increases in the urgency signal are associated with increased vigor (speed and size) of the movement (Thura et al., 2014)

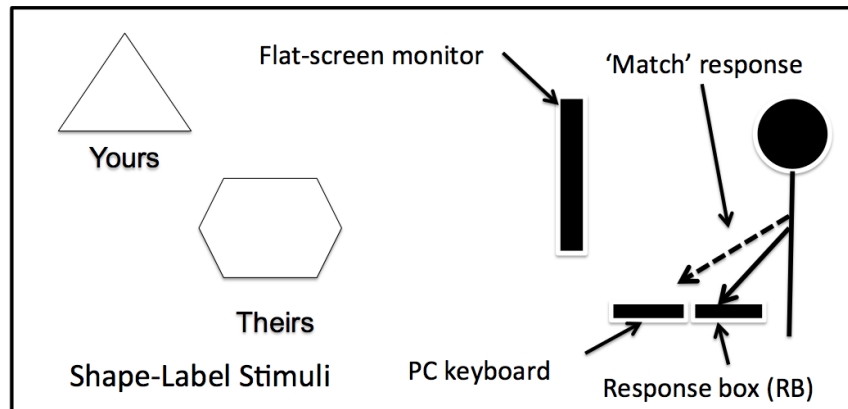
<sup>5</sup> Five participants were tested in pilot phase of the study in which procedural parameters (such as the movement response time limit) were adjusted and to achieve power at .80 with a large effect size  $d_z = 0.80$  at  $\alpha$ -value of .05. These data were not included in the final analyses.

Previous RT studies reported a large self-bias effect ( $d_z > 0.80$ ; Sui et al., 2012). MT has not been previously measured, so a medium-to-large effect size ( $d_z = 0.65$ ) with a probability of  $1 - \beta = .80$  and an  $\alpha$ -value of .05 required a minimum sample-size of 21 participants; actual power with  $N = 30$  was  $1 - \beta = .93$ . (G\*Power 3.1 program; Faul, Erdfelder, Buchner, & Lang, 2009).

## 2.2 Stimuli and tasks

The participants had to associate two geometric shapes (i.e. triangle, square, circle, hexagon, octagon, or pentagon, each subtending  $3.2 \times 3.2$  deg of visual angle) with two labels ('yours' vs. 'theirs'), following a Latin Square design. Shapes were presented on a grey background above a red fixation cross ( $1.4 \times 1.4$  deg of visual angle) shown at the centre of the screen. The personal label ( $3.1 \times 1.6$  deg of visual angle) was displayed below the fixation cross.

Participants completed two sessions, 24-hours apart. They carried out a shape-label matching task in each session, judging whether the shape-label pairings matched by releasing the right-positioned response box button using their right hand and pressing 'm' on a PC QWERTY-keyboard with their index finger. Participants used their right-hand for match judgements; and their left-hand for mismatch judgements. For mismatch judgements, participants released the left-positioned response-box button and pressed 'b' with their index finger. Hand-match judgement assignments were swapped in the second session. The order of hand-match sessions was counterbalanced across participants. The set-up elicited an arm movement away from the body, at a 20-degree tilt towards the body midline, along the axial plane covering a distance of 14cm (see *Figure 1*).



*Figure 1.* The experimental set-up and example stimuli. Participants used one hand to make ‘match’-judgment responses, and the other hand to make ‘mismatch’-judgment responses.

The experiment was run using E-Prime software (Version 2.0) on a PC, and a 24-in. LCD monitor (1920 x 1080 pixels at 100 Hz). A Cedrus RB-530 response-box recorded release-time responses.

Before the computer task, participants completed questionnaires measuring individual differences on self-related dimensions (for example, ‘personal distance’; Sui & Humphreys, 2015). The data from these instruments will be analysed and presented as part of a future separate study.

### 2.3 Procedure

The participants first read on-screen text instructing them to memorize the shape-label pairings. For example, they were told ‘the square belongs to you’; and ‘the octagon belongs to the stranger’. After this, the matching task was conducted. Participants were instructed to respond as rapidly as they could, and that there would be a response time-limit. Twenty-four practice trials were presented and a performance-accuracy threshold was set at 60%. In each trial, a central fixation cross was presented for 2000 ms; followed by a shape-label pairing for

100 ms, within a total frame duration (initiation-response time limit) of 1100 ms. The next frame was blank, with a duration (response-execution time-limit) of 1250 ms. The participants depressed both response-box buttons continuously with their index fingers until the shape-label stimulus appeared, then made a judgement-response by releasing the button under one finger and rapidly moving their arm to the target-key. Next, a blank frame for 800 ms allowed the participant to retract their arm and place their index finger back on the 'home' button before receiving feedback (*correct, incorrect, or too slow*), presented on the screen for 500 ms at the end of each trial. Inter-trial intervals were 900-1300 ms. After the practice-block, there were four blocks of 80 trials separated by an 8000 ms break, where each condition (self-matched, self-mismatched, stranger-matched, stranger-mismatched, with mismatched trials defined by the shape presented) occurred equally often, generated at random. Thus, there were 80 trials per condition. The participants were informed of their overall accuracy at the end of each block.

## 2.4 Design

There were three within-participant factors, on two levels: Association (self, stranger), Hand (left, right), and Matching-condition (match, mismatch). There were four main output measures in the two-stage response: Reaction-time (RT; measured from stimulus onset to the release of the relevant response box button); Movement Time (MT; measured from the release of the response-box button to the depression of the target key); Response Initiation Accuracy (the proportion of trials with correctly-initiated responses); and Movement Response Completion (the proportion of trials on which the movement component of correct release responses culminated in successfully hitting the target key within the time limit). In previous studies (e.g. Sui & Humphreys, 2017), a measure of the difference between self- and



stranger-related match responses has been indexed as the difference in performance of the self- versus stranger- condition, divided by the sum across the two conditions (i.e. given by the formula: “(stranger – self) / (stranger + self)”). We also used this index to compare the relative magnitudes of the self-bias across response initiation and execution components.

## 2.5 Data Analysis

For the RT analysis, only correct response initiations were analysed, and those faster than 200ms were excluded, eliminating 9.00% and 0.01% (220) of the trials, respectively. For the MT analysis, only correct movement responses following a correct release-response were analysed, and those greater than 2.5 standard deviations from individual means were excluded<sup>6</sup>, eliminating a further 2.00% and < 0.01% (173) of the trials, respectively. Thus, RT analyses were conducted on 91% of the trials, and MT analyses on 89%. See *Table 1* for means and standard deviations of RT, MT, and proportion of correctly initiated, and completed responses for each condition.

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<sup>6</sup> A minimum movement time cut-off was not applicable since correct movement responses could not be executed erroneously too quickly.

**Table 1**

Mean MTs and RTs (in ms) and Accuracy (proportion of correct responses), with standard deviations, as a Function of Association (Self vs. Stranger), Hand (Left vs. Right), and Match Condition (Matched vs. Mismatched).

Performance indices	Hand	Match condition	
		Matched	Mismatched
RTs			
Self	Left	657 (73)	752 (66)
Self	Right	637 (63)	754 (64)
Stranger	Left	758 (77)	765 (64)
Stranger	Right	763 (67)	763 (59)
MTs			
Self	Left	838 (90)	924 (76)
Self	Right	807 (67)	914 (78)
Stranger	Left	930 (96)	936 (74)
Stranger	Right	922 (73)	921 (76)
Response Initiation accuracy			
Self	Left	0.99 (0.02)	0.95 (0.06)
Self	Right	0.97 (0.03)	0.94 (0.06)
Stranger	Left	0.89 (0.08)	0.93 (0.05)
Stranger	Right	0.90 (0.07)	0.93 (0.06)
Movement response completion accuracy			
Self	Left	0.95 (0.04)	0.88 (0.08)
Self	Right	0.97 (0.03)	0.90 (0.07)
Stranger	Left	0.85 (0.11)	0.89 (0.09)
Stranger	Right	0.84 (0.12)	0.89 (0.07)

Note. RT = Reaction time, MT = movement time. Standard deviations appear within parentheses. Accuracy = proportion correct.

Effect sizes were calculated using partial eta-squared ( $\eta^2$ ) for ANOVAs and Cohen's  $d_z$  for t tests (Cohen, 1988; Lakens, 2013). Holm-Bonferroni corrections for  $\alpha = .05$  were applied to all multiple comparisons (Holm, 1979).

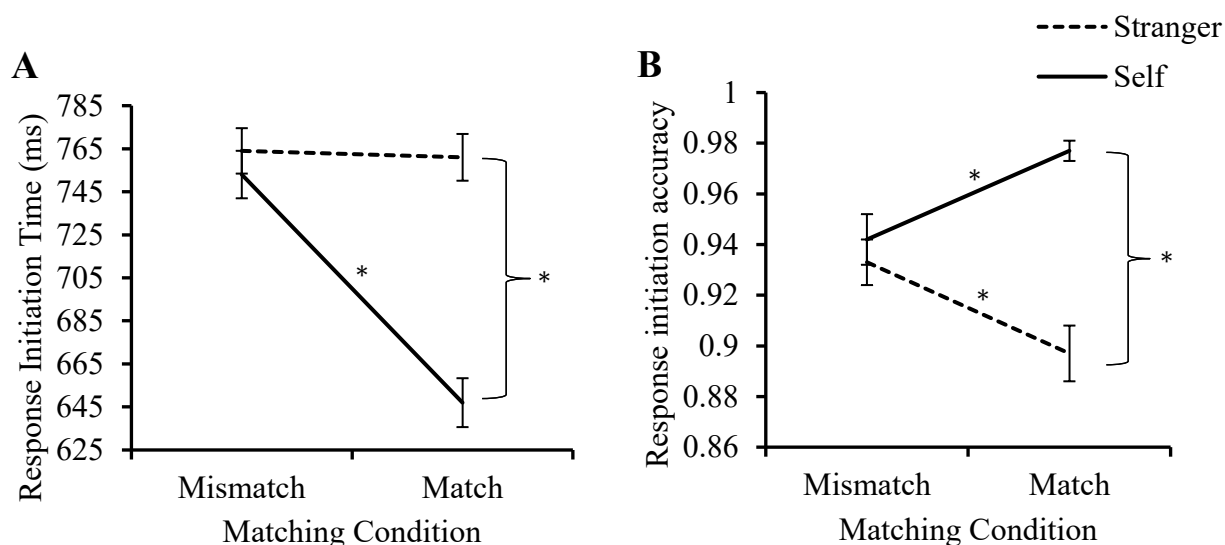
### 3. Results

**Reaction-time (RT).** A 2 (Association: Self vs Stranger) x 2 (Match condition: Matched vs. Mismatched) x 2 (Hand: Left vs. Right) repeated-measures ANOVA for MTs revealed a significant main effect of Association,  $F(1, 29) = 149.78, p < .001, \eta^2 = .84$ ; responses on self-related trials were initiated faster than on stranger-related trials. There was also a significant main effect of Match,  $F(1, 29) = 151.21, p < .001, \eta^2 = .84$ ; responses on matched-pair trials were initiated more quickly than on mismatched-pair trials. There was no significant main effect of Hand ( $p = .275$ ); and no interaction between Hand and Match ( $p = .629$ ), or between Association and Hand ( $p = .329$ ). However, there was a significant interaction between Association and Match,  $F(1, 29) = 109.69, p < .001, \eta^2 = .79$ .

The hand condition was collapsed, and pairwise comparisons revealed a significant advantage in RT for self- versus stranger-associated shape-label matching pairs,  $p < .001, d_z = 2.44$ . There was no significant difference between self- versus stranger-associated shape-label mismatching pairs,  $p = .039, d_z = 0.39$  (Holm-Bonferroni-corrected), or stranger-related matched and mismatched trials ( $p = .589$ ), but there was a significant difference between self-matched and -mismatched trials,  $p < .001, d_z = 2.78$ ; responses to self-associated matched-pair trials were faster than to self-associated mismatched-pair trials. There was no three-way interaction between Association, Hand, and Match ( $p = .130$ ).

These findings (see *Figure 2A*) replicate the original RT paradigm studies (Sui et al., 2012). Responses were initiated more quickly when responding to self- as compared with stranger-related matching shape-label pairs.

**Response initiation accuracy (proportion correct).** An ANOVA conducted on response initiation accuracy revealed: That is, there was a significant main effect of Association,  $F(1, 29) = 49.53, p < .001, \eta p^2 = .63$ ; accuracy (proportion of correctly initiated responses) was higher for self- than for stranger-related trials. This indicated that verifications for self-related trials were more accurate. There was no main effect of Hand ( $p = .326$ ) or Match ( $p = .944$ ), and no interaction between Association and Hand ( $p = .156$ ) or Hand and Match ( $p = .855$ ), but there was a significant interaction between Association and Match,  $F(1, 29) = 30.70, p < .001, \eta p^2 = .51$ . There was no three-way interaction ( $p = .397$ ). The Hand condition was collapsed and the interaction between Association and Match decomposed using pairwise comparisons: this revealed a significant difference in response initiation accuracy between stranger- versus self-related matched-pair trials,  $p < .001, dz = 1.33$ , and no significant difference in the accuracy of response initiation between stranger-versus self-related mismatched pair trials ( $p = .109$ ). There was a significant difference between the self-related matched and mismatched trials,  $p < .001, dz = 0.83$ , and a significant difference in accuracy between the stranger-related matched and mismatched trials,  $p = .001, dz = 0.69$ . Responses were most accurate on self-related matched trials, and least accurate on stranger-related matched trials. (See *Figure 2B*).



**Figure 2.** Estimated Marginal Means (with Hand condition collapsed) of: (A) Reaction-Time as a Function of Association (Self vs. Stranger) and Matching condition (Matched- vs. Mismatched-pair trials); (B) Response initiation Accuracy as a Function of Association (Self vs. Stranger) and Matching Condition (Matched- vs. Mismatched-pair trials). Error bars represent standard errors.  $*p < .002$ . Accuracy = proportion correct.

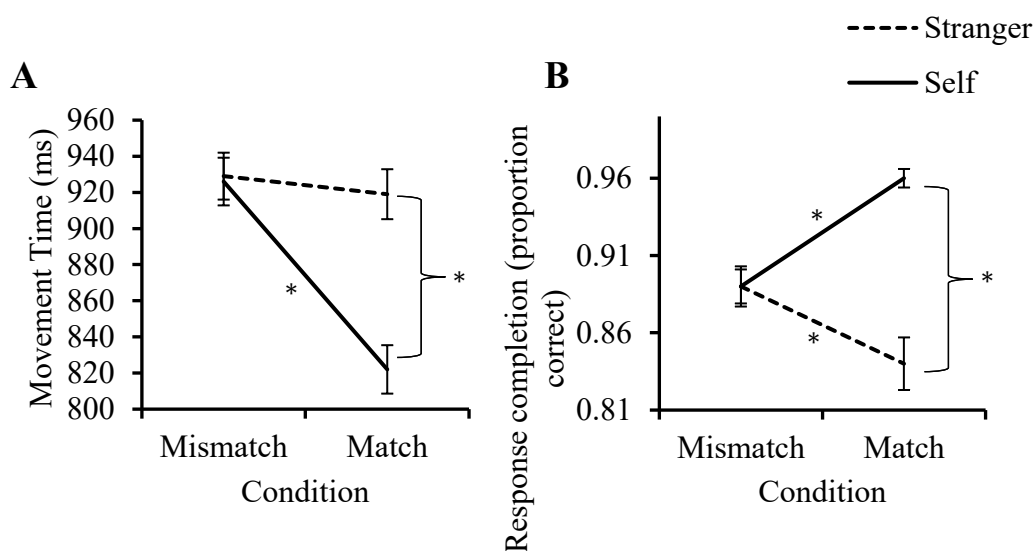
**Movement time (MT).** A 2 (Association: Self vs Stranger) x 2 (Match condition: Matched vs. Mismatched) x 2 (Hand: Left vs. Right) repeated-measures ANOVA for MTs revealed a significant main effect of Association,  $F(1, 29) = 154.90, p < .001, \eta^2 = .84$ ; participant responses were faster to the self-association than to the stranger-association. In contrast to the RT findings, there was a significant main effect of Hand,  $F(1, 29) = 23.69, p < .001, \eta^2 = .45$ ; the movement component of participants' responses was faster when using the right (dominant) hand as compared with the left (non-dominant) hand. However, as with the RTs, there was a significant main effect of Match,  $F(1, 29) = 129.68, p < .001, \eta^2 = .82$ ; responses to Matching pairs were faster than to Mismatching pairs. Similarly, there was no

interaction between Hand and Match ( $p = .991$ ), or between Association and Hand ( $p = .397$ ), and there was a significant interaction between Association and Match,  $F(1, 29) = 106.75$ ,  $p < .001$ ,  $\eta p^2 = .79$ . This indicated that, as with the RTs, there was a different pattern in the execution of responses to the self- versus stranger-associated shapes dependent on whether they were presented in Matched- or Mismatched-pair trials. There was no three-way interaction between Association, Hand, and Match ( $p = .307$ ) (see *Figure 3A*).

These results show that MT followed the same pattern across hands as RT in terms of an advantage for self, except that, in contrast to RT findings, left-hand responses were slower across conditions (this is consistent with the finding that right-handed participants' dominant hand aiming movements tend to be quicker and more accurate; Olex-Zarychta & Raczek, 2008).

The Hand condition was then collapsed and the Association and Match interaction decomposed using pairwise comparisons. This revealed a significant difference in the movement time of responses to the matching self- versus stranger-associated shape-label pairs,  $p < .001$ ,  $d_z = 2.46$ ; responses to the matched self-associated pairs were faster than to the matched stranger-associated pairs. There was no significant difference between the movement time in responses to the mismatching self- versus stranger-associated shape-label pairs,  $p = .049$  (after Holm-Bonferroni correction). There was no significant difference in movement latencies between responses to stranger-associated matched and mismatched pairs ( $p = .627$ ). However, there was a significant difference between responses to the self-associated matched and mismatched pairs,  $p < .001$ ,  $d_z = 2.78$ ; responses to the matched self-associated pairs were faster than to the mismatched self-associated pairs.

Movement responses to self-associated matched pairs were faster than in any other condition. There was no difference in responses across the stranger-match and mismatch conditions. The advantage for matching-self-associated pairs driving the interaction between the Association and Match conditions is represented in *Figure 4A*.



**Figure 4.** Estimated Marginal Means (with Hand condition collapsed) of: (A) Movement Time as a Function of Association (Self vs. Stranger) and Matching condition (Matched- vs. Mismatched-pair trials); (B) Proportion of correctly-completed movement responses as a Function of Association (Self vs. Stranger) and Matching Condition (Matched- vs. Mismatched-pair trials). Error bars represent standard errors. \* $p < .001$ .

**Movement Response Completion (proportion correct).** ANOVA on movement response completion (proportion correct; see *Design*) data revealed a similar pattern to Response Initiation Accuracy: there was a significant main effect of Association,  $F(1, 29) = 61.90, p < .001, \eta p^2 = .68$ ; accuracy was higher for self- compared with stranger-related responses. In contrast to the MT data, there was no main effect of Hand ( $p = .377$ ), or Match

( $p = .130$ ). Like with MTs, there was no interaction between Association and Hand ( $p = .193$ ), or Hand and Match ( $p = .686$ ), and no three-way interaction between Association, Hand, and Match ( $p = .713$ ). However, as with the MT and response initiation accuracy data, there was a significant interaction between Association and Match,  $F(1, 30) = 41.71$ ,  $p < .001$ ,  $\eta p^2 = .59$ . Therefore, the Hand condition was collapsed, and the interaction probed using pairwise comparisons. As with the Response initiation accuracy data, this revealed a significant difference in response completion accuracy on self- versus stranger-related matching-pair trials,  $p < .001$ ,  $dz = 1.33$ , and no significant difference between self- versus stranger-related mismatching-pair trials ( $p = .177$ ). There was also a significant difference between self-related matching and mismatching pair trials,  $p < .001$ ,  $dz = 0.83$ , and, in contrast to the MT data, but similarly to the response initiation accuracy data, between stranger-related matching and mismatching trials,  $p = .001$ ,  $dz = 0.69$ .

Movement responses on self-related matching-pair trials were more accurate than in any other condition. In contrast to the MT data, there was a difference in responses across the stranger-match and both mismatch conditions: Responses were least accurate in the stranger-matched-pair condition (i.e., when neither the self-label nor self-shape was presented). The interaction between Association and Match conditions driven by the advantage in accuracy on self-related match trials compared to mismatch trials, and the disadvantage in accuracy on stranger-related match compared with mismatch trials, is depicted in *Figure 4B*.

**Signal detection (sensitivity) indices for response initiation.** In a supplementary analysis, and in order to provide a more sensitive measure of response initiation accuracy performance, a signal-detection approach was adopted. Performance in the match conditions was contrasted with performance in the mismatching conditions (with the same shape) to compute sensitivity index D Prime ( $d'$ ; see Sui et al., 2012).



The  $d'$  indices were submitted to a 2 (Association: Self vs Stranger) x 2 (Hand: Left vs. Right) repeated-measures ANOVA which revealed a significant main effect of Association,  $F(1, 29) = 58.99, p < .001, \eta p^2 = .67$ ; sensitivity for the self-related condition was higher than on stranger-related trials. There was no significant main effect of Hand ( $p = .065$ ). However, there was a significant interaction between Association and Hand,  $F(1, 29) = 5.27, p = .029, \eta p^2 = .15$ .

The interaction was decomposed, and pairwise comparisons revealed no significant difference between left- and right-handed stranger-related responses ( $p = .914$ ), but a significant advantage in sensitivity for right-handed stranger-associated ( $M = 3.11, SD = 0.87$ ) versus right-handed self-associated ( $M = 3.89, SD = 1.04$ ) responses,  $p < .001, dz = 0.85$ ; between left-handed stranger- ( $M = 3.10, SD = 0.94$ ) versus left-handed self-related ( $M = 4.38, SD = 0.96$ ) responses,  $p < .001, dz = 1.30$ ; and between left-handed self- ( $M = 4.38, SD = 0.96$ ) and right-handed self-related ( $M = 3.89, SD = 1.04$ ) responses,  $p = .013, dz = 0.48$ .

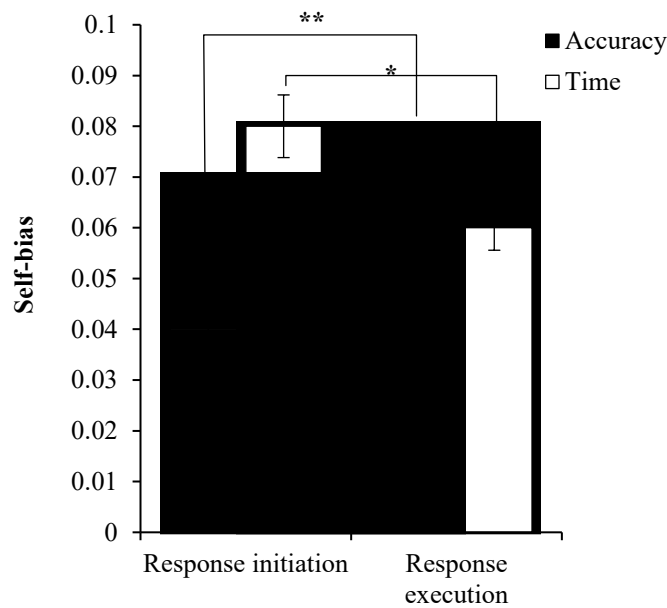
These results support the findings from the analysis of response initiation accuracy – self-related responses had a sensitivity advantage over stranger-related. However, in contrast, the sensitivity index revealed a significant interaction across hands driven by a significant difference between left- and right-handed self-related responses, with an advantage for left-handed initiation responses. (Implications of this finding remain for future studies to elucidate. For example, accounts might appeal to an interaction between the SRE and hemispheric specialization for domains of self-processing and the preparatory and motor control mechanisms that differ across hand-motor networks. However, such accounts would introduce new material and a broader discussion that would detract from the core research question). The reliability of this finding and its implications could be explored in future

studies.

### **Comparing responses across the RT-interval and execution phases.**

Using a measure of ‘self-bias’ (given by the formula: “(stranger – self) / (stranger + self); see Methods section) we used this index to compare, next, the relative magnitudes of the self-bias across response initiation and execution components. If there were no differences across the response initiation and execution components, this would give some indication that effects were likely to have been predominantly driven by the heightened saliency of the self-stimuli (and, as such, via a common mechanism across response initiation and execution). In other words, the respective propulsions of the self- versus stranger-related responses relative to each other would remain unchanged through to response completion. If there were differences across the response phases, however, this would suggest that self-reference may interact with more than one mechanism during the preparation and execution arm-movement responses (see *Introduction*).

A paired-samples t test revealed a significant difference in self-bias between RT ( $M = 0.08$ ,  $SD = 0.03$ ) and execution time ( $M = 0.06$ ,  $SD = 0.02$ ),  $t(29) = 9.855$ ,  $p < .001$ ,  $dz = 1.80$ ; self-bias in response time was significantly greater in response initiation than in response execution. A paired-samples t test was then conducted to test for a difference between the magnitude of self-bias in accuracy across response initiation ( $M = 0.04$ ,  $SD = 0.03$ ) and execution ( $M = 0.07$ ,  $SD = 0.05$ ): A significant difference was found,  $t(29) = 3.50$ ,  $p < .001$ ,  $dz = 0.64$ ; however, in contrast to response-time self-bias, accuracy self-bias was greater in the movement component of responses (see *Figure 5*). The implications of these findings are considered in the *Discussion*.



**Figure 5.** Magnitude of the self-advantage in proportional accuracy and response time as a function of response phase (RT-interval vs. execution processes). Error bars represent standard error.  $**p < .001$ . Accuracy = proportion of trials in which responses were correctly released / executed.

#### 4. Discussion

This study tested whether the self-reference effect (SRE) can influence the execution of forward-motion rapid-aiming arm-movement responses. A simple two-handed motor-variant of Sui et al.'s (2012) shape-label (self vs. stranger) perceptual-matching procedure using a 'home' and target-key set-up (Praamstra et al., 2014; Jensen & Munro, 1979) was

devised to measure RT (from stimulus onset to release of the home key) and MT separately over a 14cm-distance (from home-button-release to target-key depression). Self- and stranger-related trials were compared, and a distinct advantage in the speed (MTs) of correctly-executed responses on self-related trials was found. In addition, the proportion of correctly-executed responses for self- as compared with stranger-related trials was significantly greater. An SRE in RTs was also found, replicating previous findings (Sui et al., 2012).

In line with our hypotheses, the faster MTs and a higher proportion of correctly-executed responses observed in the self-match condition indicate that the SRE modulated response execution processes. The SRE could potentially influence response preparation, the urgency/initiation signal (Haith et al., 2016; Weinberg, 2016), or online control (Khan et al., 2006). We ruled out that the urgency/initiation signal alone was modulated. Therefore, we present a novel demonstration that the SRE can enhance the execution of rapid-aiming arm-movement responses.

The aim of the current study was to determine *whether* the SRE can influence response execution processes. It remains for future studies to determine *how* the SRE modulates action. Since execution processes involve both response preparation and online control, future work is needed to unpick how the SRE interacts with these processes. For example, tracking modification of trajectories during online correction could determine online control effects (Khan et al., 2006). Similarly, analysing kinematics of the limb trajectories and parsing the movements into their initial impulse and error correction phases, and measuring the directional error (before the influence of visual and proprioceptive feedback), would provide valuable information pertaining to the quality of the response programming, for example (see Khan et al, 2006).

From a theoretical perspective, the ‘social saliency’ effects of self-reference on perceptual processing (Humphreys & Sui, 2015; 2016), in conjunction with previous findings regarding saliency effects on motor processes (e.g. Schmidt et al., 2006; Ulrich et al., 1998), raise a strong possibility that preparatory activity during self-match responses could have been enhanced via bottom-up driven processing. SAT mechanisms in premotor processing (influencing the information accumulation rate) may directly modulate EMG recruitment (i.e. the late stages of motor processing) – speeded responses can increase the rate of EMG-activity build-up (Speiser, Servant, Hasbroucq, & Burle, 2017). However, such a boost to response execution may be qualitatively distinct from effects so far examined in RP studies given the involvement of a dedicated self-processing network (Humphreys & Sui, 2016; Sui et al., 2013b), which, for example, has been shown to support effects that are dissociable from those of (e.g.) perceptual saliency.

One finding from the current study that sheds some light on whether the SRE may simply be a saliency-driven effect is that self-bias in response time was significantly smaller in MTs than RTs, and the self-bias in correctly-completed responses was significantly higher in the response execution as compared with its initiation. If the relative ‘saliencies’ of self- as compared with stranger-related responses driving the bottom-up effects were the only factor influencing response execution, it would be expected that the self-bias (as an index of the relative magnitude of the difference; see Method section) would remain unchanged in response execution given that self- and stranger-match use the same effector/task response. However, the current study findings were not consistent with this. In other words, the proportion of correctly-completed responses in movement did not simply reflect the proportion of correct-release responses. This suggests that the SRE interacts with the

different mechanisms operating during the two response phases; in other words, that the SRE modulates response execution through more than one mechanism. Again, future studies are needed to unpick effects of (e.g.) perceptual saliency as compared with the SRE on response execution.

Another account for the speed-accuracy differences across self- and other-person-related responses is that the latter are more difficult (Fuentes, Sui, Estévez, & Humphreys, 2015; Humphreys, 2015). Activity in the dorsal attention control network during stranger-match responses (Sui et al., 2013) is consistent with increased attention required for the task (Humphreys, 2015). In further support of this, when a differential outcome procedure (which facilitates learning of difficult associations) was integrated into Sui and colleagues' matching task, the SRE was extinguished when supportive feedback was exclusively provided in the other-person as opposed to self-related condition (Fuentes et al., 2015). Difficulty also affects motor processes. When decisions are more difficult, they have been shown to take longer and movement preparation build up more slowly (Weinberg, 2016). Therefore, stranger- relative to self-related responses were delayed, perhaps due to a more slow-building preparatory activity that was not completed by the time the urgency signal activated the release (accounting for the lower proportion of correctly-completed responses and longer RTs; see Haith et al., 2016; Weinberg, 2016). In contrast, the shorter RTs for self-related responses, yet with no cost for correct movement completion (relative to stranger-related responses), suggested (following Haith et al., 2016; and in line with the second option detailed in the study hypotheses) that self-related responses were (more) fully-completed on release. It could be that if preparatory activity in self-related responses is boosted via the initial rapid feedforward sweep (Schmidt et al., 2006), the threshold for release is met before the general

task demands (see Thura & Cisek, 2017; e.g., response time-limit) increase the urgency signal and meet that threshold<sup>7</sup> (see Weinberg, 2016). In self-related responses, therefore, preparation and initiation could effectively be yoked, and preparation could determine RT, thus optimising rapid responses. Such mechanisms remain to be investigated in future studies.

One finding of note was that the proportion of correctly-completed responses across the RT-interval and execution phase were significantly lower for stranger-match responses as compared with mismatch responses; whereas, RT and MT were not significantly different across these conditions. Differences across conditions are likely to be underpinned by differential response strategies/decision criteria and neural network recruitment by the stimuli shape-label elements in the four conditions (self-match, stranger-match, and shape-based self-mismatch, and stranger-mismatch; Sui et al., 2012; Sui et al., 2013b; Sui et al., 2014; Sui & Humphreys, 2017). Analysis of responses on mismatch trials in an imaging study (Sui et al., 2013b), for example, revealed that the self-label exclusively activated the vmPFC, the self-label and self-shape were associated with activity in the pSTS, whereas responses on stranger-match trials activated the dorso-lateral pre-frontal cortex. The shape-label combinations therefore recruit different circuitry. If the ‘self’ elements prime the match-hand response (Humphreys & Sui, 2016), this initial response in the mismatch conditions must be suppressed by top-down fronto-parietal attentional control; if unsuccessful, a response error is generated (Humphreys & Sui, 2016).<sup>8</sup> This could be attributed to the general (global) urgency signal that would increase in the context of speeded tasks (see Thura & Cisek, 2017),

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<sup>7</sup> The urgency signal is adjusted as a function of task context (Thura et al., 2014).

<sup>8</sup> Bottom-up priming drives effects of feature-based attention (Theeuwes, 2013).

in conjunction with the primed ‘self’ response, which would result in the threshold for release arriving too quickly for it to be inhibited by top-down control and the slower recurrent processing.<sup>9</sup> In contrast, the response putatively triggered via the initial feed-forward sweep in the self-match condition does not need to be suppressed, and the recurrent processing in its wake (Schmidt et al., 2006) simply boosts the (congruent) movement response, further enhancing it.<sup>10</sup> Similarly, in the neuroscience literature it has been found that movements initiated earlier tend toward default responses (Haith et al., 2016). Furthermore, in the self-match condition, the shape-label conjunction may prime the response rather than combined effects of the separate shape and label (features). Conjunctions, not features, are bound to the self (Schafer et al., 2016), and it is this processing, unique to the self-match condition, that could account for the superior (bottom-up driven) enhancement putatively reflected in this condition.<sup>11</sup>

The stranger-match condition involves no self-elements, and errors necessarily require generation of the ‘non-self-primed’ hand response, so errors in this condition are not likely to be driven by a self-priming-like mechanism. Instead, we contend that they are likely to be driven by interference from the superior binding-like action of self-reference (Sui, 2016). Previous studies have suggested that self-associations tend to dominate expectancies (Sui et al., 2014) and, due to a glue-like initial binding (including between different

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<sup>9</sup> In the current study, no differences were found across self- versus stranger-related mismatch conditions, but it should be noted that a handful of previous studies have incidentally found small, but significant differences. Future research could examine in what task contexts these differences can arise.

<sup>10</sup> In RP, if the prime stimulus is mapped to same response as the target stimulus (i.e., in compatible trials), responses are faster and more accurate than when different responses are mapped to these stimuli (i.e., incompatible trials) (Bermeitinger & Wentura, 2016).

<sup>11</sup> Once learned, conjunctions can modulate bottom-up perceptual processing of the stimulus (Reavis, Frank, Greenlee, & Tse, 2016). A holistic perception of the stimulus may be bound to the self (e.g. paralleling automatic face processing; see Schafer et al., 2015).



processing stages) can interfere with associations between other stimuli and that self-linked response (Wang, Humphreys, & Sui, 2016; see also Humphreys & Sui, 2016; Sui, 2016). In the context of the current task, errors in the stranger-match condition may be in some sense be repelled by the self-binding and sent toward the non-self-linked effector. Therefore, the lower accuracy in the stranger-match as compared with mismatch condition could reflect that suppressing the ‘self-priming’ in a mismatch response may be more straightforward than overriding the interference from self-binding effects during a stranger-match response.

Self- as compared to stranger-related responses might also differ with respect to how much top-down control is involved in their execution, and at what point this takes control of responses. Large priming effects are observed when factors such as (e.g.) saliency boost the initial rapid bottom-up processes of the ‘feedforward sweep’ (Schmidt et al., 2006); in other words, these processes drive movement execution for longer before top-down recurrent processing takes over control (see e.g., Schmidt & Seydell, 2008). In the current study task, the top-down control required to produce *correct* mismatch- and stranger-match responses would necessarily need to take control of responses prior to their release (to remain correct). In contrast, the execution of rapid self-related responses may only become top-down controlled once the movement itself is underway (and recurrent processing has had time to take effect; Schmidt & Seydell, 2008). Slower responses due to task difficulty are less likely to be feed-forward driven (although there may still be an element of rapid-chase processing in very slow tasks; Schmidt & Schmidt, 2009). In other words, whereas non-self responses may be entirely top-down controlled, released by the urgency signal; self-related responses may initially be bottom-up driven, and driven to release by preparatory activity.

Future experiments using RP and kinematic analysis paradigms are needed to test

these possibilities and would shed light on the effects of self-reference on response preparation versus execution. Furthermore, pitting established priming effects (e.g. perceptual saliency) against self-reference would elucidate (any) qualitative differences between the SRE and effects so far identified in RP. If self-reference generates dissociable effects from established response priming (just as effects have been dissociated at perceptual level in the SRE literature – e.g., Liu and Sui [2016]), this would be evidence that the SRE could similarly activate rapid responses (see e.g., Schmidt et al., 2011).

The topic of how the SRE can influence action is fascinating and ripe with possibilities. The current study provides a first insight into these possibilities and presents a novel demonstration that the SRE can modulate the execution of rapid arm-movement responses. Elucidating the mechanisms underlying the SRE in action is a topic for future research. The hope is that the current study will inspire systematic investigation of how the SRE modulates action; for example, via exploration of kinematics and trajectory effects (see Khan et al., 2006) and through RP paradigms (see Schmidt et al., 2011; Schmidt & Seydell, 2008).

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