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Predictable and self-initiated visual motion is judged to be slower than computer generated motion

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ABSTRACT

Self-initiated action effects are often perceived as less intense than identical but externally generated stimuli. It is thought that forward models within the sensorimotor system pre-activate cortical representations of predicted action effects, reducing perceptual sensitivity and attenuating neural responses. As self-agency and predictability are seldom manipulated simultaneously in behavioral experiments, it is unclear if self-other differences depend on predictable action effect contingencies, or if both self- and externally generated stimuli are modulated similarly by predictability. We factorially combined variation in (1) predictability of action effects, (2) spatial congruence, and (3) performance by the self or computer to dissociate these influences on a visual discrimination task. Participants performed 2AFC speed judgments. Self-initiated motion was judged to be slower than computer-initiated motion when action effect contingencies were predictable, while spatial congruence influenced speed judgments only when action effect contingencies were unpredictable. Results are discussed in relation to current theories of sensory attenuation.

1. Introduction

The sensory consequences of voluntary actions, henceforth "action effects", are often perceived differently from identical but externally generated stimuli. This general finding has been conceptually replicated in several sensory modalities. Self-initiated action effects, for instance stimuli triggered by a button press or other voluntary movement, are judged to be less loud (Sato, 2008; Weiss, Herwig, & Schütz-Bosbach, 2011), less forceful (Bays, Wolpert, & Flanagan, 2005; Shergill, Bays, Frith, & Wolpert, 2003), and less ticklish (Blakemore, Wolpert, & Frith, 1998; Claxton, 1975) than equivalent stimuli initiated by another person or mechanical apparatus. Self-initiated action effects are also perceived differently from external events with respect to their timing. Compared to externally triggered stimuli, there is a perceived shortening of the temporal interval between an intentional action and its effect, a phenomenon known as intentional binding (Engbert & Wohlschläger, 2007; Haggard, Clark, & Kalogeras, 2002).

Similar findings have been reported at the neural level. For example, the sounds of one's own speech elicit a reduced blood oxygen level dependent (BOLD) response in auditory cortex compared to listening control conditions (Christoffels, van de Ven, Waldorp, Formisano, & Schiller, 2011). Self- and externally initiated action effects have also been compared by means of ERPs (e.g. Baess, Widmann, Roye, Schroger, & Jacobsen, 2009; Hughes & Waszak, 2011; Martikainen, Kaneko, & Hari, 2005). The N1 is a negative deflection around 100–150 ms post stimulus thought to be associated with early cortical

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processing of sensory stimuli. Self-initiated action effects evoke lower amplitude N1 responses compared to externally generated stimuli. For example, Baess et al. (2009) found a reduced auditory N1 for self-initiated tones, and Hughes and Waszak (2011) found attenuated cortical responses over frontal and parietal areas to self-initiated visual effects starting around 150 ms post stimulus. These results suggest cortical sensory attenuation occurs at an early stage in perception, with the caveat is that no study has simultaneously assessed phenomenological and neurophysiological indices of attenuation.

The different experiential qualities of self-initiated action effects are normally explained in terms of predictive forward models within the sensorimotor system (see Waszak, Cardoso-Leite, & Hughes, 2012 for a review). Forward models predict the future state of a system, for instance, an upcoming perception, based on a combination of current sense data (i.e. the current state of the world), outgoing (efferent) motor signals, and knowledge about the likely consequences of an action in a particular environment based on past experiences (Körding & Wolpert, 2004). A proposed mechanism to explain attenuation of self-initiated action effects is that action preparation triggers a forward model which activates perceptual areas representing the predicted action effect (Waszak et al., 2012). This prior activation makes the objective presence or absence of incoming sensory signals less discriminable (or intense), compared to situations with no prior predictions, or an incorrect prediction. An implication is that sensory attenuation should not be observed, or should be less pronounced, when an action effect turns out differently than expected, or when the statistical properties of an environment make it difficult to predict the action effect. Consistent with this account, sensory attenuation may be reduced or absent when action effects are temporally delayed (Bays et al., 2005; Blakemore et al., 1998) or incongruent with expectations (Cardoso-Leite, Mamassian, Schütz-Bosbach, & Waszak, 2010). This suggests sensory attenuation is linked to specific external events caused by self-generated movements, rather than movements per se. By contrast, intentional binding does not seem to depend on specific action effect predictions, as similar binding effects occur for both congruent and incongruent action effects (Desantis, Hughes, & Waszak, 2012). Thus sensory attenuation and intentional binding may rely on different mechanisms.

There has been some question whether sensory attenuation is a unique property of self action, or alternatively results from a more general predictive mechanism that could generalize to other types of perceptual events (e.g. Lange, 2011; Sato, 2008). To investigate the specific role of self-agency in sensory attenuation, Weiss, Herwig, and Schütz-Bosbach (2011) compared the perceived loudness of predictable tones that were either self-initiated, or produced by another person or computer agent. They found that self-initiated tones were judged to be less loud compared to the other conditions. This suggests perception is influenced by processes recruiting by performing actions, such as efferent motor signaling or a sense of agency. However, all the tones during the test phase were congruent with the prior acquisition phase, so it is uncertain whether predictability and congruence would also modulate the perceived intensity of externally generated tones. In an ERP study by Gentsch, Kathmann, and Schütz-Bosbach (2012), participants were briefly presented with primes which were either congruent or incongruent with subsequent visual events, for both low and high contingency conditions. Attenuation of the visual N1 in the self-initiated condition was modulated by prime-effect congruence for both low and high contingency conditions. However, in the externally generated condition, the prime-effect congruence only influenced the N1 in the high contingency condition. Thus, there is some evidence that that congruence and predictability may influence perception of external stimuli differently from self-initiated action effects.

To summarize, self-initiated action effects often have a unique perceptual quality that distinguishes them from external stimuli which seems to depend on specific sensory predictions generated during voluntary actions. A recent review of the literature concluded that several factors likely play a role in sensory attenuation, including motor prediction, temporal predictability and control, action effect congruence, and top-down beliefs about one's causal agency (Hughes, Desantis, & Waszak, 2013a). Some studies emphasize the role of action effect congruence (e.g. Cardoso-Leite et al., 2010; Lally, Frendo, & Diedrichsen, 2011) while others emphasize the self-other distinction (e.g. Sato, 2008; Weiss et al., 2011). However, no study to date has simultaneously investigated the effects of internal vs. external origin (i.e. self-initiated vs. externally triggered), statistical predictability, and congruence of the action effect using behavioral measures of perception, as opposed to ERP. The theoretical contribution of such a study would be to disentangle these known influences on perception. For example, it's unclear whether self-initiated and externally generated stimuli are similarly modulated by predictability (i.e. the strength of contingency between a triggering event and its effect) and/or the congruence of the action effect. Another question is whether perceived differences between self-initiated and externally triggered events might remain even when action effects are unpredictable. For example, in one ERP study, self-initiated tones evoked a reduced N1 even when they were temporally unpredictable (Lange, 2009). Furthermore, top-down knowledge about one's status as a causal agent appears to enhance sensory attenuation (Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012). These findings suggest the possibility that self-initiated action effects might be attenuated compared to externally generated stimuli regardless of predictability, provided the actor feels a sense of agency for the action effect.

The purpose of the present study was to distinguish the influences of self origin, predictability, and action effect congruence on perception of a visual action effect. To this end, we factorially combined (1) variation in predictability of action-effect contingencies, (2) spatial congruence of action effects, and (3) performance by the self or a computer. The specific action effect relationship we investigated was the perceived speed of a moving stimulus triggered by key press. In everyday life, the onset of motion is a particularly salient action effect which often marks the beginning or end of an event. For this reason motion stimuli are frequently used to study the perception of causality (see Wagemans, van Lier, & Scholl, 2006 for a review). In a previous study, participants' ability to detect coherent motion in a random dot motion display was influenced by the spatial congruence of self-generated arm movements with respect to an array of moving distracter dots (Lally et al., 2011). This indicates that visually-defined motion is subject to sensory attenuation as a result of sensorimotor predictions