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Bioelectrical brain effects of one's own voice identification in pitch of voice auditory feedback

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ABSTRACT

Control of voice fundamental frequency (F0) relies in part on comparison of the intended F0 level and auditory feedback. This comparison impacts "sense of agency", or SoA, commonly defined as being the agent of one's own actions and plays a key role for self-awareness and social interactions. SoA is aberrant in several psychiatric disorders. Knowledge about brain activity reflecting SoA can be used in clinical practice for these disorders. It was shown that perception of voice feedback as one's own voice, reflecting the recognition of SoA, alters auditory sensory processing. Using a voice perturbation paradigm we contrasted vocal and bioelectrical brain responses to auditory stimuli that differed in magnitude: 100 and 400 cents. Results suggest the different magnitudes were perceived as a pitch error in self-vocalization (100 cents) or as a pitch shift generated externally (400 cents). Vocalizations and neural responses to changes in pitch of self-vocalization were defined as those made to small magnitude pitch-shifts (100 cents) and which did not show differential neural responses to upward versus downward changes in voice pitch auditory feedback. Vocal responses to large magnitude pitch shifts (400 cents) were smaller than those made to small pitch shifts, and neural responses differed according to upwards versus downward changes in pitch. Our results suggest that the presence of SoA for self-produced sounds may modify bioelectrical brain responses reflecting differences in auditory processing of the direction of a pitch shift. We suggest that this modification of bioelectrical response can be used as a biological index of SoA. Possible neuronal mechanisms of this modification of bioelectrical brain response are discussed.

1. Introduction

1.1. Experience of one's own control of vocalization

The control of vocalization has been of interest as it pertains to speech and singing for a number of years. In recent times, this control process has received additional attention through the advent of techniques that measure how a speaker reacts to perturbations in sensory feedback of vocal output. In most cases, vocal and neural responses were measured in response to alterations in auditory feedback of vocal pitch. One aspect of this technique that has not received full attention involves the "Sense of Agency" (SoA) related to a speaker's voice.

The SoA, is referred to as the experience of oneself as the agent of one's own actions (agency), or in other words the sense that "I am the one who is causing or controlling a movement or change(s) in the outside word that I am perceiving" (for more details see: Gallagher, 2000; Moore, 2016). SoA plays a key role in self-awareness (Gallagher, 2000), body-awareness (Haggard and Tsakiris, 2009; Kannape and Blanke, 2012), and social interaction (De Jaegher and Froese, 2009; Ruys and Aarts, 2012). Recent advances in SoA studies (for more details see: David, 2012) suggest that SoA is a complex and dynamic, multi-layered, and multifactorial phenomenon that involves multiple sensory systems, various brain areas, and complex interactions between these areas. Although several theoretical accounts for the SoA were suggested (Moore, 2016; Synofzik et al., 2008a, 2008b; Synofzik et al., 2013) and scientific investigations of SoA constitute a rapidly expanding field (David et al., 2015), the neuronal mechanisms of the SoA are not well understood (Blakemore and Frith, 2003; David et al., 2008; Haggard and Chambon, 2012; Moore and Haggard, 2008; Weiss et al., 2011). In the present study we examine the issue of SoA related to voice control.

The neuroscientific operationalizations of SoA during voluntary actions utilize explicit and/or implicit measures (Moore, 2016; Moore et al., 2012; Saito et al., 2015; Synofzik et al., 2008a). Explicit measures employ explicit judgments of whether a sensory event is caused by one's own action or results from events in the outside word. The implicit

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aspect of agency is a non-conceptual, usually unconscious "low-level feeling" of being an agent that is closely related to self-caused action regulation or perceptual processing (Saito et al., 2015). Therefore for the implicit measures of SoA, the experiences of action are simply tagged as self-caused or not (Moore et al., 2012). There is no objective, biological index for the process of implicit agency registration. Based on our everyday life observations on SoA, this process was described as the following: "Rather than being explicitly aware of the motor representations, in moment to moment situations we experience self-agency by a rather diffuse sense of a coherent, harmonious ongoing flow of anticipations and sensory feedback" (Pacherie, 2001). It was hypothesized that this implicit level of internal action-monitoring might be defective in clinical cases (Pacherie, 2001). Therefore, bioelectrical indexes of SoA associated with involuntary, reflexive actions are needed for clinical practice. The advantages of bioelectrical indexes of SoA elicited by involuntary, reflexive actions over explicit judgments about SoA following voluntary actions are obvious in light of the results showing that SoA is not "given" when people produce apparently voluntary actions (Wegner and Sparrow, 2004). Specifically, it was reported that explicit SoA is a fragile construct that is dependent on inferences about which agent was the most probable cause of the action and what purpose or meaning the action had (Moore et al., 2009; Wegner and Wheatley, 1999).

Meta-analysis of brain hemodynamic changes associated with SoA suggested that the temporo-parietal junction, pre-supplementary motor area (SMA) and pre-frontal cortex might be involved in a network underlying SoA (Sperduti et al., 2011). In line with this, studies of voluntary actions also suggest that the pre-SMA (known for its role in action planning and initiation) might be one of the crucial brain areas for the subjective experience of agency (Cavazzana et al., 2015; Javadi, 2015; Kuhn et al., 2013; Moore et al., 2010). Apparently, connectivity between SMA and parietal brain areas might underlie the experience of SoA (Dogge et al., 2014; Ritterband-Rosenbaum et al., 2014).

A critical function for SoA is evident from clinical studies showing that lesions to the pre-SMA in humans can lead to alien-limb syndrome, with patients demonstrating involuntary actions such as grasping nearby objects - even other people - without ever intending to do so (for review see: Della Sala et al., 1991; Feinberg et al., 1992; Sarva et al., 2014). Moreover, the capacity to experience SoA might be impaired in certain pathological conditions, in which patients regularly fail to identify their own actions or thoughts, by misattributing them to external sources. This phenomenon was extensively studied in patients with schizophrenia (Asai and Tanno, 2008; Frith and Done, 1989; Kircher and Leube, 2003; Maeda et al., 2012; Robinson et al., 2016; Spence et al., 1997; Waters and Badcock, 2010) and results suggest that delusions of influence are based on imprecise internal predictions about the sensory consequences of one's actions (Ford and Mathalon, 2012; Frith, 1987; Synofzik et al., 2010). Aberrant SoA was also found in patients with obsessive-compulsive disorder (Gentsch et al., 2012a, 2012b) and in individuals with autism spectrum disorders (Chiu et al., 2008; Uddin et al., 2008). Also, borderline personality disorder (BPD) patients have dysfunctional self-image/identity (Leichsenring et al., 2011), and diagnostic criteria for BPD specify that a person must have a significant impairment in personality functioning in relation to self. Thus an identity disturbance appears to be a core and distinctive component of BPD with patients expressing a sense of "self-fragmentation" and "falling apart" (Wilkinson-Ryan and Westen, 2000).

Internal predictions about one's actions are theoretical constructs that have been shown to be valuable in understanding control of several types of behaviors (Blakemore et al., 2002; Frith et al., 2000). For example, when a person is speaking, if the sound of the auditory feedback of one's voice matches what the speaker intended to say, there is a modification of bioelectrical brain activity, which has been interpreted to mean that the brain recognizes the voice as self produced (Hawco et al., 2009; Korzyukov et al., 2015; Scheerer et al., 2013). Moreover the study of SoA for speech indicates that auditory feedback of our own voice acts as a pathway for semantic monitoring (Lind et al., 2014). These results suggest that voice-related SoA might arise from central processing incorporating internal predictions of one's vocalizations.

1.2. *Control of self-vocalizations and "sense of agency"*

One of the main ways in which vocalizations are controlled is by monitoring the acoustical properties of the voice to insure its accuracy and if necessary, to correct for errors in production (Chang et al., 2013; Greenlee et al., 2011; Houde et al., 2002; Rauschecker, 2011). This process involves the use of SoA to identify self-vocalization, which requires the act of vocalizing and recognizing a close similarity between what the speaker intended to produce and the sensory feedback of the voice. At the behavioral level recognition of the auditory input as one's own vocalization is acoustically expressed as an appropriate corrective involuntary change in vocalization (e.g., voice pitch) in response to an unintentional aberration in voice auditory feedback. If the auditory feedback is not recognized as self-produced, the sound is treated by the brain as any other environmental sound, there is no SoA experience and the motor corrective actions are small in magnitude.

In concert with these studies, it has been shown that bioelectric signals representing brain activity may be sensitive to the issue of self-produced vs. externally-produced speech sounds. Previous studies showed that the N1 component of Event Related Potentials (ERP) is suppressed for small pitch shifts (100 cents) while the N1 is not suppressed for large pitch shifts (400 cents) in voice auditory feedback. Moreover, large pitch shift magnitudes elicit ERPs that vary in magnitude according to stimulus direction (up or down pitch shift) whereas ERPs to small magnitude pitch shifts do not vary according to stimulus direction (Liu et al., 2011a; Liu et al., 2011b). Therefore, measuring ERPs in response to voice pitch-shifted auditory feedback can be used as an indicator of SoA.

Motor control models (for review see: Haggard, 2005) suggest that SoA seems to arise from the integration of information about predicted feedback, sensory information, and efferent copies of motor control neural signals. One of the important elements of this mechanism is the modulation of sensory input during self-generated movement. For example the study of finger-muscle activity in the SMA associated with SoA suggests that this brain area provides an efferent signal to modulate somatosensory activity during self-generated movement (Haggard and Whitford, 2004).

Taking into account studies suggesting that the vocal motor system can modulate auditory cortical processing (Behroozmand et al., 2016, 2015; Chang et al., 2013; Cogan et al., 2014; Daliri and Max, 2016; Greenlee et al., 2013; Jenson et al., 2015; Sitek et al., 2013) we hypothesized that during vocalization, SoA-related motor activity should alter functional characteristics of auditory perceptual neuronal networks. Specifically we hypothesized that there should be a difference between bioelectrical brain responses with and without the presence of SoA associated with vocalization. Quantification of this difference potentially can be used as a bioelectrical index of SoA in clinical practice.

Several ERP studies of SoA associated with vocalization have demonstrated that if the vocal sound is recognized as self-produced, there is suppression of neural activity (N1 ERP component) related to auditory processing of the sound (Behroozmand and Larson, 2011; Curio et al., 2000; Flinker et al., 2010; Ford et al., 2001; Heinks-Maldonado et al., 2005; Houde et al., 2002). Similar to audition, SoA-related suppression mechanisms have been observed in the visual modality. For example a reduction of the visual N1 ERP response has been observed as a marker of a self-produced action as compared to externally generated feedback (Gentsch et al., 2012a, 2012b; Gentsch and Schutz-Bosbach, 2011). These studies support our hypothesis that if auditory processing is altered by the act of self-produced action, the functional characteristics of auditory processing neurons should be