Intrinsic and extrinsic influences on self-recognition of actions

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Abstract

Despite minimal visual experience and unfamiliar third-person viewpoints, humans are able to recognize their own body movements even when actions are reduced to point-light displays. What factors influence visual self-recognition of own actions? To address this question, we recorded whole-body movements of a large sample of participants ($N = 101$) performing a range of actions. After a delay period, participants were tested in a self-recognition task: identifying own actions depicted in point-light displays amongst three other point-light actors performing identical actions. While participants showed above-chance accuracy on average for self-recognition, we found substantial differences in performance across actions and individuals. Self-recognition performance was modulated by interactions between extrinsic factors (associated with the degree of motor planning in performed actions) and intrinsic traits linked to individuals' motor imagery ability and sensorimotor self-processing ability (autism and schizotypal traits). These interactions shed light on mechanistic possibilities for *how* the motor system may augment vision to construct the core of self-awareness.

Keywords: self-recognition, body movement, action, individual differences, self-awareness

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Public Significance Statement:

In this large-scale study on self-action recognition, we demonstrate how motor mechanisms influence self-recognition of own actions beyond visual features. Our individual difference approach further introduces novel interactions between intrinsic participant and extrinsic motor factors during self-action recognition.

Introduction

Recognition of oneself depends on more than visual experience. As a prime example, humans can recognize their own actions from minimal visual input provided by point-light action displays (Cutting & Kozlowski, 1977; Loula et al., 2005; Beardsworth & Buckner, 1981)— disconnected dot animations depicting the motion of key joints on the human body (Johansson, 1973). Despite removal of body identity information and the depiction of actions from an unfamiliar third-person perspective, self-recognition from point-light movements suggests that people can readily connect motor experience of performing actions to visual recognition of actions. This finding is consistent with multiple lines of evidence that have revealed close links between motor and visual representations of actions (e.g., Binet, 1886; Viviani & Stucchi, 1992; Prinz, 1997; Knoblich & Flach, 2001; Casile & Giese, 2006; Rizzolatti, Fogassi, & Gallese, 2001; Blake & Shiffrar, 2007).

Previous research has identified a few core characteristics of self-recognition from actions. From point-light actions, participants are more accurate in recognizing themselves than visually familiar friends (Cutting & Kozlowski, 1977), even when configural topographic cues are disrupted (Cook, Johnston, & Heyes, 2012; cf. Loula et al., 2005), or visual feedback is removed (Casile & Giese, 2006). People can identify their own actions from hand movements (Conson, Aromino & Trojano, 2010) and from whole-body movements (Loula et al., 2005). Self-recognition of one's own gait is viewpoint-invariant (cf. Mitchell & Curry, 2016), but recognition of familiar friends from their gait patterns is viewpoint-dependent, with better performance from frontal than profile views (Jokisch, Daum & Troje, 2006). View-independent performance for self-recognition from point-lights has also been observed for actions less common than walking (Loula et al., 2005; Burling et al., 2019), suggesting that visual representation of self-actions based primarily on motor experience is fundamentally different from the action representation of others learned from visual experience. Furthermore, the self-action advantage extends beyond explicit visual recognition, influencing the predictive accuracy of future action

outcomes (e.g., Knoblich & Flach, 2001; Bischoff et al., 2012; cf. Hohmann et al., 2011), task-irrelevant, body part recognition (Frassinetti et al., 2009; Daprati & Sirigu, 2002; Daprati, Weriessneggeer, & Lacquaniti, 2007), facial expression recognition (Cook, Johnson & Heyes, 2012), memory for self-performed action verbs (i.e., enactment) (Engelkamp & Krumnacker, 1980), and multimodal action recognition (e.g., Repp & Knoblich, 2004; Flach, Knoblich, & Prinz, 2004; Murgia et al., 2012; Kennel et al., 2014).

While these studies reveal the importance of the motor experience for self-action recognition, further research is needed to pin down exactly how the motor system contributes to self-action recognition. Several limitations of previous studies must be addressed. First, studies of self-recognition from point-light movements have all utilized relatively small sample sizes of participants (in the range of 6~34). Second, there lacks systematic assessments as to how different actions influence self-recognition performance across different actions, although some previous studies demonstrated the presence of such item-level influences (Loula et al., 2005; Sevdalis & Keller, 2009; Burling et al., 2019). Loula et al. (2005) included ten actions in their study and found that self-recognition performance varied across individual actions, with more accurate self-recognition for visually complex actions such as dancing or boxing, than walking/running. Sevdalis and Keller (2009) found greater self-recognition performance for improvised dancing compared to stereotyped gait patterns. Coste et al (2020) asked participants to perform postural motions with general instructions, such as “create postural motions by keeping knees extended with toes and heels in constant contact with the floor.” The study found that people more often misidentified themselves for movements that showed high similarity between self and other actions. However, these studies have yet to systematically manipulate and compare actions with different levels of perceptual variability, that are more specifically modulated by the degree of motor planning required by the action goal (e.g., Molnar-Szakacs et al., 2006; Li et al., 2020). Third, beyond item-level variability in action stimuli, another limitation in the literature on self-action recognition

relates to the impact of intrinsic traits at the participant level—opting for group-level rather than individual differences. To date, only one behavioral study from our group (Burling et al., 2019) has examined the impact of autistic traits on self-action recognition performance. However, the study focused on group comparisons by selecting participants with extremely high or low autistic traits, while neither mapping out any other individual difference measures nor including a large sample of participants to examine the variability of individual differences in self-action recognition.

To address the prior limitations, we conducted the first large-scale study ($N = 101$) in self-action recognition to examine how motor-based mechanisms, linked to extrinsic factors of action stimuli, interact with intrinsic traits of participants to impact self-recognition of actions. To assess extrinsic influences that may impact item-level variability in self-recognition, the present study included a larger range of actions, varying complexity based on the degree of motor planning involved in performing actions. To examine intrinsic influence of participant-level variability, we assessed the relationship between self-recognition performance and three individual difference measures: autistic, schizotypal, and motor imagery traits.

Numerous studies have shown atypical self-processing in two prevalent clinical conditions: Autism Spectrum Conditions (ASC) – from the Greek root “autos” for self (Kanner 1943; Asperger, 1944; Perrykkad & Howhy, 2020), and Schizophrenia Spectrum Conditions (SSC), a “disordered self”, characterized by “a disunity of consciousness” (Bleuler, 1911; Schneider 1959; Sass & Parnas, 2003; Kraepelin 1919; Parnas & Herniksen, 2014; Sandsten et al., 2020). Recent research has attributed these types of atypicalities to a specific alteration in sensorimotor self-processing in clinical populations (e.g., Noel et al., 2016; Sass & Borda, 2015; Gallese & Ferri, 2014; Gessaroli et al., 2013; Perrykkad and Howe, 2020). Researchers have suggested that own-body discrimination manifests in contrasting ways in ASC and SSC (Noel, Cascio, Wallace, & Park, 2016), and appears to relate to sharpened or blurred internal self/other boundaries, respectively (Noel et al., 2016; Fletcher & Frith, 2009). Consistent with

73 sensorimotor characterizations of self-processing in ASC and SSC, converging studies in biological
74 motion perception also reveal atypical performance patterns in action recognition related to both clinical
75 disorders (e.g., Hur et al., 2016; Wang et al., 2018; Blain, Peterman, & Park, 2017; Ferroni et al., 2020;
76 Thakkar et al., 2011).

77 Many findings of perceptual atypicalities in clinical populations have been extended to
78 individual differences in the broader spectrum of autistic traits and schizotypal traits within the general
79 population (Miller & Saygin, 2013; Puglia & Morris, 2017; Thurman et al., 2016; van Boxtel et al.,
80 2017; Wang et al., 2018; Chakraborty & Chakrabarti, 2015). The prototypical measurement of self-
81 reported autism-spectrum traits in the general population is the Autism-Spectrum Quotient (AQ)
82 questionnaire (Baron-Cohen et al., 2001). Recent evidence has identified an overlapping genetic and
83 biological etiology underlying ASC and autistic traits (Bralten et al., 2017), in addition to behavioral
84 overlap (Baron-Cohen et al., 2001). Several studies have reported a relation between AQ scores and
85 performance in a range of tasks related to biological motion perception (e.g., Miller & Saygin, 2013;
86 Ahmed & Vander Wyk, 2013; van Boxtel, Peng, Su, & Lu, 2017, Blain, Peterman, & Park, 2017).
87 Similarly, researchers have developed individual measures of schizotypy traits assessed by the
88 Schizotypal Personality Questionnaire (SPQ) (Raine, 1991), which estimates vulnerability toward
89 developing schizophrenia, i.e., “psychosis-proneness” (Johns & Van Os, 2001; Vollema et al., 2002).
90 Schizotypal traits capture stable forms of the pathology (Widiger, 2012) and the spectrum of SSC in the
91 neurotypical population (Torbet, Schulze, Fiedler, & Reuter, 2015; Siever & Davis, 2004). Previous
92 research has also reported a relation between SPQ scores and performance on action recognition tasks
93 (e.g., Blain, Peterman, & Park, 2017; Kim et al., 2011).

94 In addition to autistic and schizotypal traits, we included motor imagery ability as a third intrinsic
95 factor. Motor imagery serves as a part of a simulation network, triggered either through visual observation
96 or through self-imaging, since action recognition and simulation share overlapping neural and behavioral

resources (Jeannerod & Pacherie, 2004). We assessed motor imagery ability using the Vividness of Motor Imagery Questionnaire-2 (Roberts, 2008) as a potential source of individual variability in self-recognition of actions. This factor was examined for several reasons. First, recognition of one's own action requires an egocentric (first-person) to allocentric (third-person) spatial simulation of one's own body (e.g., Ganesh, Schie, Cross, Lange, & Wigboldus, 2015), and self-processing recruits motor imagery mechanisms (e.g., Conson et al., 2010). Second, action perception and motor imagery representations share common neural resources (Miller & Saygin, 2013; Iacoboni & Dapretto, 2006; Clark, Tremblay, & Ste-Marie, 2004; Grèzes & Decety 2001), impacting variability in the general population on biological motion tasks (Miller & Saygin, 2013). In addition, both SSC and ASC have been linked to atypical motor simulation ability (e.g., Oberman & Ramchandran, 2007), with likely extensions to the general population.

The experimental design consisted of two sessions. In the first session, 27 actions performed by each participant were recorded through motion capture. Participants were informed that their actions were being recorded for an action recognition study, but were never informed of study's focus on self-recognition. Eighteen actions were verbally instructed (i.e., "please naturalistically perform the action: *to grab*"), and the other nine actions were elicited by video instruction, asking participants to imitate body movements of an actor shown in a video. We included video instruction since imitation presents a unique action requirement: integrating observed visual information with one's internal motor system (i.e., observation of others performing actions and action production with self-body movements). Additionally, action imitation involves lessened motor planning, due to copying another's motor sequence (see enactment effect; Zimmer & Engelkamp, 1996). If self-recognition performance depends primarily on the degree of motoric planning involved in performing actions, we would expect that imitation actions may yield lower accuracy in identifying own body movements than actions with verbal labels. Using videos to prompt participants to imitate actions further removes the potential influence of individual differences in language comprehension or in interpretation of semantic labels of actions.

After a delay of about one month on average, participants returned to complete a self-recognition task that required identifying their own action among three other actors performing the same action. We hypothesized that participants would be able to self-recognize most actions above chance, and self-recognition performance would be influenced by both extrinsic factors – action types linked to motor planning (Loula et al., 2005; Burling et al., 2019) – and intrinsic factors, linked to sensorimotor self-processing based on individual differences in autistic traits, schizotypal traits and motor imagery ability. To further separate the impact of motor experience from visual experience in self-action recognition (speculated upon in Loula et al., 2005), we included an additional visual recognition task in which participants were asked to recognize previously-seen actions in the imitation condition.

Method

Participants 108 undergraduate students ($M_{\text{age}} = 21.20$, $SD_{\text{age}} = 3.81$, females = 79, males = 29) were recruited through the Subject Pool at the University of California, Los Angeles. Sample size was determined in accord with a previous study on the relation between emotion discrimination from the gait patterns and autistic and schizotypy traits (e.g., Blain, Peterman, and Park, 2017). The study was approved by the UCLA Institutional Review board. All participants were provided course credit for their participation and were naïve to the purpose of the study. Participants had normal or corrected-to-normal vision and no physical disabilities. Seven participants were excluded due to inputting errors of participant motion capture files, resulting in a total of 101 participants included in the analysis ($M = 28$, $F = 73$).

Apparatus Participants' body movements were recorded using the Microsoft Kinect V2.0 and Kinect SDK in a quiet testing room. Here, participants were instructed to perform the actions in a rectangular 0.76 m x 1.52 m space, in order to provide flexibility to perform the action, while remaining within recording distance. The Kinect was placed 1.52 m above the floor and 2.59 m away from the participant.

The three-dimensional (X-Y-Z) coordinates of the key joints were extracted at a rate of approximately 33 frames per second and later used to generate point-light displays of actions (see Figure 1). Customized software developed in our lab was utilized to enhance movement signals, and to carry out additional processing and trimming for actions presented later in the testing phase (van Boxtel & Lu, 2013).

Stimuli Generation. All actions were selected to be commonly encountered actions and were captured by the motion capture system. The actions varied in complexity in order to characterize a broad range of common movements in daily life. First, participants performed nine simple and nine complex actions provided with clear verbal labels (i.e., verbal instruction). Simple and complex actions were extended from Burling et al (2019), delineated by whether the action was a simple goal (e.g., *wave*), conveying a routine action with less motor planning, or a complex goal (e.g., *argue*) linked to more detailed motor planning. The simple actions included *grab, jump, wave, lift, kick, hammer, push, point, punch*. The complex actions included: *argue, macarena, wash windows, play baseball, get attention, hurry up, fight, stretch, and play guitar*.

In addition, participants were performed actions based on video instruction. Participants were asked to view an action performed by actors shown in a stick-figure display (i.e., lines connected between joint positions) on a computer, and subsequently imitate the seen action afterwards. Nine imitation actions were selected from the Carnegie Mellon Graphics Lab Motion Capture Database available online (<http://mocap.cs.cmu.edu>), generated from pre-defined actors. The actions were selected to capture a broad range of goal variability: *jumping jacks, basketball, bend, direct traffic 1, direct traffic 2, conversation, laugh, digging a hole, and chopping wood*. To account for any implicit goal-attribution or familiarity with action sequences that could impact the degree and/or type of imitation (e.g., Bekkering et al., 2000; Wöhlshägel et al., 2003; Wild et al., 2009), we also included a range of familiar (e.g., *bend*) and unfamiliar (e.g., *directing traffic*) imitation action sequences. Participants were never provided the

verbal label for imitation actions. Each video displayed an actor shown as a stick figure performing one of the imitation actions and was presented in three different angles to the subject, either to the right or left ($\pm 45^\circ$; half-profile) or facing forward (0° ; frontal) by rotating the horizontal axis. Each imitation action was recorded twice: once after viewing the three different angles, and once more after viewing only the forward-facing angle. The first imitation recording was discarded (served as practice during motion recording), and only the second imitation recording was used in the self-recognition experiment. The recorded raw motion data from the Kinect system were passed through a double exponential adaptive smoothing filter (LaViola, 2003) to remove noisy and jittered movements (e.g., ballistic random jump of points). Additionally, the stimuli were trimmed and processed to display the point light-displays using BioMotion Toolbox (van Boxtel & Lu, 2013) with their segmented action recording, which would be reiteratively looped in the self-recognition session.

Procedure

The experiment was split into two phases: motion recording and recognition. The first phase consisted of a motion recording session, where participants performed the actions and were recorded with a motion capture system. Participants were informed that their actions were recorded for an action recognition study and were never informed about the aim of the study. After a delay period ($M = 37.39$ days, $SD = 5.20$ days; range: 23 – 56 days), participants returned for the second phase to complete two recognition tasks. In the first task, participants completed a self-recognition task by identifying their own actions that were recorded with the motion capture system. In the second task, participants completed a visual recognition task, where they identified the actions imitated during the motion recording session (further elaboration below). The order of the self-recognition task and the visual recognition task was counterbalanced between participants.

Motion Recording Phase

For the 18 simple and complex actions in the first recording session, participants were provided verbal instruction and asked to perform the actions as naturally as possible (i.e., “please naturalistically perform the action: *to grab*”). For the remaining nine imitation actions, none of the participants were provided the verbal label of the action. Instead, participants were instructed to *imitate* the movements of the action presented in a stick figure video.

Figure 1. Illustration of motion recording. *Left*, actions were recorded by the Kinect system and converted to point-light displays; *Right*, an example frame of imitation action videos by an actor shown in a stick-figure display. Participants were asked to imitate the seen actions.

After completing the action recording, participants completed two questionnaires: Schizotypal Personality Questionnaire (SPQ; Raine, 1991) and the revised Vividness of Motor Imagery Questionnaire (VMIQ-2; Roberts et al., 2008). The SPQ was administered to assess degrees of schizotypal traits among individuals in the typical population. The VMIQ-2 was included to assess motor imagery differences as a potential source of variability in self-processing and biological motion processing.

Recognition Phase: Self-Recognition Task and Visual-Recognition Task

In the second phase (recognition test), participants were seated approximately 0.76 meters in front of a monitor in a dimly lit room and were asked to select their own action amongst three other distractor actions spread out horizontally along the center of the screen, as shown in Figure 2. Each action was presented with 25 point-lights located at key joints, in three different orientations (rotated around the vertical axis 0°, (frontal), 45° (half-profile, right), 225° (half-profile, left), for a total of 81 trials. All of the actions within a trial displayed the same orientation. The actions were looped until the participant

selected one of the four horizontally-spread, randomly arranged boxes, or until a time period of 30 seconds. Participants were not provided any feedback. Participants were instructed to select their own point-light action amongst four displays. The four animations included their own action and the same action performed by three distractor actors with the same gender, all of whom participants were unfamiliar with. All the point-light actions were normalized for maximum height. Following selection of the action, participants were asked to provide a confidence judgment, in which they rated the confidence of their selection from 1 (not at all confident) to 5 (most confident).

Figure 2. Schematic illustration of a sample trial showing wave action for the self-recognition task. One point-light action is the participant's action, while the other three point-light actions are distractors performed by gender-matched actors. During the display of actions, participants were provided a maximum of 30 seconds to click on the action that was their own. Following the actions, participants rated their overall confidence in the selection (1: not at all confident to 5: most confident).

The first 28 participants were tested with only the self-recognition task. The subsequent 73 participants were tested with both self-recognition task and an additional visual recognition task consisting of nine trials displaying only the forward-facing imitation actions. Participants were instructed to identify the stick-figure actor they imitated during the motion recording phase (converted to point-light display) amongst three other distractor point-light actors who performed the same action, that were identical to

those used in the self-recognition task. The inclusion of this visual recognition task allowed us to assess whether recognition performance would differ when delineating self-generated from visually observed actions. Importantly, while the stimulus layout of the task was identical to the self-recognition task, the participants' own action from the self-recognition task was replaced by the original imitation actor from the motion capture database, consequently introducing prior visual experience. As a result, participants never viewed their own self-generated action in the visual recognition task. The order of presentation of the visual recognition task was counterbalanced to either follow or precede the self-recognition task. Following the self-recognition and visual recognition task, participants were asked to complete the Autism-Spectrum Quotient (AQ) questionnaire to assess their degree of Autistic traits (Baron-Cohen et al., 2001).

Individual Difference Measures

Autistic Quotient ASC resides on a spectrum of psychopathology. We assessed self-reported autism-spectrum traits in the general population using the Autism-Spectrum Quotient (AQ) questionnaire, consisting of 50 questions designed to measure five different subtypes: *social skill*, *attention switching*, *attention to detail*, *social communication*, and *imagination* (Baron-Cohen et al., 2001). Response criteria requires the selection of one of the four possibilities (four-point scale): “definitely disagree”, “slightly disagree”, “slightly agree”, “definitely agree.” While not a diagnostic instrument, scores of 32+ on the AQ in the general population are generally indicative of a predisposition to ASC, out of a maximum score of 50 points (1 point per question validating autism-spectrum traits), while the cutoff for ASC individuals on the AQ is typically greater than 26 (Woodbury-Smith, Robinson, Wheelwright, & Baron-Cohen, 2005; Ruzich et al., 2016).

Schizotypal Personality Questionnaire To assess predisposition to Schizotypal Personality Disorder in the neurotypical population, we used the Schizotypal Personality Questionnaire (SPQ) developed by Raine

(1991). The 74-item survey was based on criteria from the *DSM-III-R* (American Psychiatric Association, 1987) to measure schizotypy from multiple dimensions (positive, negative, disorganized, and paranoia) and capture its phenotype, etiology, symptomatology (Wuthrich and Bates, 2006; Barron et al., 2015). We opted for the full-scale SPQ (74 items) rather than the more recent SPQ-brief (32 items; Cohen et al., 2010), as the original SPQ has been shown to provide a clearer division of the individual subscales (Ford and Crewther, 2014), important when considering the reflected overlap between AQ and SPQ subscales. The SPQ adopts a three-factor structure (analogous to the symptom structure in Schizotypal Personality Disorder and SSC), measuring three main constructs of schizotypy: the cognitive-perceptual dimension (positive schizotypy), interpersonal dimension (negative schizotypy), and disorganized feature dimension (disorganized schizotypy) based on *DSM-III-R* criteria (Raine, 1994), but well-matched to current *DSM-V* criteria (Barron et al., 2015). Further divisions within the three-factor structure include nine different subscales of the SPQ: *ideas of reference, unusual perceptual experiences, odd/magical beliefs, suspiciousness/paranoid ideation* (cognitive-perceptual); *social anxiety, no close friends, constricted affect* (interpersonal); *odd behavior and appearance, and odd speech* (disorganized) (Raine 1991; 1994). Response criteria on the questionnaire requires binary selection of “true” or “false” (two-point scale) to particular statements (e.g., “I am aware that people notice me when I go out for a meal or to see a film”). Top 10% of scorers reflect scores greater than 41, while the bottom 10% typically score 12 or lower.

Vividness of Motor Imagery Questionnaire The VMIQ-2 (Roberts, 2008) measures introspective reports of vividness of imagery in kinesthetic (movement simulation), internal (first person simulation), and external (third person simulation) visual imagery of 12 different actions (e.g., kicking). Vividness of motor imagery is rated on a five-point Likert scale for each of the 12 actions in each of the three sub-areas. Note that lower scores in VMIQ-2 indicate more vivid images and stronger motor imagery ability.

Results

Impact of action types on self-recognition performance

As shown in Figure 3, participants were able to recognize self-actions significantly above chance performance (0.25 in a 4AFC task): for simple actions with verbal instruction ($M = 0.41$, $SD = 0.16$), $t(100) = 9.45$, $p < .001$, cohen's $d = .940$, for complex actions with verbal instruction ($M = 0.54$, $SD = 0.17$), $t(100) = 16.86$, $p < .001$, $d = 1.678$, and for imitated actions without verbal instruction ($M = 0.39$, $SD = 0.16$), $t(100) = 9.20$, $p < .001$, $d = .916$, corroborating prior research (e.g., Burling et al., 2019; Loula et al., 2005). Confidence data showed consistent results with self-recognition accuracy for the action types (see supplementary materials for further detail).

A two-way repeated-measures ANOVA with action orientations and action types as within-subjects factors on self-recognition performance revealed no effect of action orientation, facing left: 225° ($M = 0.45$, $SD = 0.16$), front: 0° ($M = 0.45$, $SD = 0.14$), right: 45° ($M = 0.44$, $SD = 0.15$), $F(2, 200) = 1.58$, $p = .207$, $\eta_p^2 = .016$. The finding is consistent with a previous study showing that self-recognition of walking actions is independent of the viewing angle (Jokisch, Daum, & Troje, 2004). However, the analysis yielded a significant main effect of action type (simple, complex, and imitation), $F(2, 200) = 43.09$, $p < .001$, $\eta_p^2 = .301$. Bonferroni-corrected pairwise comparisons further revealed that self-recognition was more accurate for complex than simple actions ($t(100) = 7.86$, $p < .001$, $d = .782$) and imitation actions ($t(100) = 8.56$, $p < .001$, $d = .851$). No difference emerged between simple and imitation actions ($t(100) = 0.54$, $p = .593$, $d = .053$). We also found a significant two-way interaction between orientation and action type (Figure 3), $F(4, 400) = 2.77$, $p = .027$, $\eta_p^2 = .027$, mainly driven by the weaker performance in the frontal view than side views for the imitation actions ($F(2, 200) = 4.124$, $p = .018$, $\eta_p^2 = .040$). However, the small effect size calls for caution in interpretation of this interaction effect, as the degree of visual ambiguity due to body occlusion likely impacted self-recognition performance for certain action orientations. Among the imitation actions, three actions (e.g., bend, digging hole and chopping

wood) consisted of the most self-occlusion from the frontal view, resulting in grouping ambiguity in the point-light display.

Figure 3. Self-recognition accuracy by action types (x-axis) and orientation (colored bars). All action types recognized significantly above chance. Complex actions showed greater self-recognition performance than did simple or imitation actions. Dashed line indicates chance performance (0.25). The error bars indicate standard error of means.

Analysis of item-level variability in self-recognition performance for individual actions (Figure 4) revealed that all complex actions (*stretch*, *get attention*, *wash windows*, *argue*, *guitar*, *hurry up*, *fight*, *baseball*, and *macarena*) were self-recognized significantly above chance ($ps < .001$). Individual simple actions (*point*, *punch*, *lift*, *grab*, *push*, *hammer*, *jump*, and *kick*) except *wave*, and imitation actions (*basketball*, *conversation*, *directing traffic p1*, *directing traffic p2*, *chopping*, *digging*, and *laugh*) except *bend*, were also self-recognized significantly above chance performance ($ps < .030$).

Due to variability in performance at the individual action level, we further ran an analysis with a linear mixed effects model, including “individual actions” and “participants” as random effects and “action type” as a fixed effect. The model accounted for residual variance in the individual actions across

participants, with a significant main effect of action type on self-recognition performance ($F(2, 24) = 11.23, p < .001$), confirming the impact of the extrinsic factor based on action type.

Figure 4. Mean self-recognition accuracy as a function of the individual action. Color-coding of bars corresponds to action type: simple actions denoted in gray, complex actions denoted in white, imitation actions denoted in black. Dashed line indicates chance performance (0.25). Error bars denote standard error of the means.

To examine the extent that perceptual variability impacted self-recognition accuracy for the extrinsic action factor, we employed an analysis based on similarity measures of motion trajectories in actions, the dynamic time warping (DTW) method. DTW analysis utilizes a non-linear, monotonic warping algorithm to measure the similarity between time series data such as movement trajectories of joints (Gavrila & Davis, 1995). As DTW measures differences between movement trajectories from actions performed by different people, smaller DTW distance values indicate greater similarity of movement trajectories across participants when they performed the same action. For each participant, we extracted the 3D positions of each of the 17 joints using the BioMotion toolbox (van Boxtel & Lu, 2013)

and centered the trajectories to zero for each joint. We then used the DTW function in MATLAB to compute pairwise distances of the joint trajectories across participants. The analysis included the joints of *head, neck, clavicle, center/left/right waist, left/right shoulder, stomach, left/right elbow, left/right wrist, left/right knee, left/right ankle* for each of the nine simple and nine complex actions. For each participant, a mean distance for an action was computed by averaging across pairwise DTW distances between this participant with all other participants, and then averaged across joints for this action. Two analyses were conducted using the mean DTW distances. First, we found that the correlation between each participant's mean DTW distance and average self-recognition performance for simple and complex actions was non-significant (spearman $\rho = .120$, 95% CI $[-.078, .309]$, $p = .233$), ruling out the possibility that self-recognition performance is primarily determined by the variability of body movements of individuals who perform actions in different ways from others. In addition, we computed two mean DTW distance values for simple actions and complex actions respectively for each participant. T-tests on the mean distance values for the action types showed that movement trajectories for complex actions ($M = 3.79$, $SD = 1.27$) were significantly more variable than for simple actions ($M = 2.25$, $SD = 0.60$), $t(100) = -15.80$, $p < .001$, $d = 1.57$, consistent with the observation that visual variability generally mapped onto motor planning complexity for the action types.

Finally, we contrasted performance in the self-recognition task in comparison to performance in the visual recognition task for imitation actions. Self-generated actions present the unique case of expert motor experience (kinesthetic, proprioceptive, and muscle contraction information), but impoverished visual experience from a third-person perspective. By contrast, expertise of movement patterns in many situations, such as sports, show both superior motor ability in performance of one's own actions, but also superior visual ability in recognition of actions performed by others, such as teammates (Hohmann et al., 2011). Our task manipulation allowed for the comparison between actions that participants performed (i.e., own imitation action) versus actions that the participant observed (i.e., stick figure imitation actor).

As shown in Figure 4, participants performed at chance level for visual recognition of previously viewed actions ($M = 0.23$, $SD = 0.19$), $t(72) = -0.718$, $p = .475$, $d = -.084$, but showed much greater recognition performance in identification of one's own action ($M = 0.38$, $SD = 0.15$), with visual recognition performance significantly lower than performance in self-identification, $t(72) = 5.41$, $p < .001$, $d = .633$. The around-chance performance for actions with only visual experience confirms that prior visual experience alone may not suffice for supporting self-recognition. Identifying oneself relies on the ability to simulate the action onto one's own motor system, with visual self-recognition in turn dependent on a matching process to compare simulated action to observed action.

Figure 4. Recognition accuracy for imitation actions in the self-recognition task with motor experience versus performance in the visual-recognition task with visual experience. Significantly weaker performance from recognizing actions from visual experience than for self-recognition from performed actions. Dashed line indicates chance performance (0.25). Error bars indicate standard error of means.

Impact of intrinsic traits on self-recognition performance

The second analysis step focused on the impact of intrinsic variability in individual difference measures on self-action recognition. Two participants did not complete the VMIQ-2, and one participant did not complete the AQ questionnaire. Hence, listwise deletion resulted in 98 participants included in the individual differences analysis. Descriptive statistics for the scores of autistic traits (AQ score),

schizotypal traits (SPQ score) and motor imagery ability (VMIQ-2 score), and subscale scores are reported in supplementary materials Table 1. Independent sample t-tests revealed no significant effects of sex on composite AQ ($t(96) = 1.06, p = .293, d = .239$), SPQ ($t(96) = 0.01, p = .994, d = .002$), or VMIQ-2 ($t(96) = -0.98, p = .328, d = -.222$) scores.

We first conducted regression analyses to examine relations between composite scores of individual difference measures and self-recognition performance. For each action type (simple, complex, and imitation), self-recognition performance was set as the dependent variable and three composite scores (AQ for autistic traits, SPQ scores for schizotypal traits, and VMIQ-2 scores for motor imagery ability) were predictor variables in the regression analysis. None of the three regression models revealed significant relationships. However, nonparametric correlation analyses revealed that composite motor imagery (VMIQ-2) scores negatively correlated with self-recognition performance for imitation actions (spearman $\rho = -0.221, 95\% \text{ CI } [-.406, -.017], p = .029$) (see Figure 5). Note that lower VMIQ-2 scores indicate stronger motor imagery ability. Thus, the negative correlation between motor imagery scores and self-recognition performance in imitation condition indicates that individuals with better motor imagery ability showed greater self-recognition performance for imitation actions.

Figure 5. Relations between composite motor imagery ability and self-recognition for imitation actions. Note that lower VMIQ-2 score indicates better motor imagery ability.

Next we examined whether subscale scores in individual difference measures showed relationships with self-recognition performance. We focused on subscale scores for two reasons. First, both ASC and SSC are characterized by multidimensional symptom expression, which may be masked by the aggregate measure. Second, selected subscale scores in autistic traits and schizotypal traits have been shown to relate to atypical biological motion perception (e.g., Blain et al., 2017; Puglia and Morris, 2017) and self-processing (e.g., Ferroni et al., 2020; Thakkar et al., 2011; Lenzenweger, 2010).

To select important predictor variables from 17 subscale scores (5 subscales in AQ, 9 subscales in SPQ and 3 subscales in motor imagery VMIQ-2), we ran three stepwise regressions in relation to self-recognition performance for the three action types. For the simple action condition, the stepwise regression selected a model with four subscale scores as predictor variables (AQ *social communication*, and three SPQ subscale scores including *odd behavior*, *ideas of reference*, and *no close friends*) that showed significance in predicting self-recognition performance for simple actions ($F(4,93) = 2.817, p = 0.030$). However, among the four selected subscale scores, only AQ *social communication* scores revealed significant coefficient ($t(92) = -2.672, p = .009$). Consistently, nonparametric correlation analysis showed a negative relation between AQ *social communication* and self-recognition for simple actions (spearman $\rho = -.229, 95\% \text{ CI } [-0.414, -0.026], p = .023$) (see Figure 6). As higher AQ scores indicate more autistic traits, the negative correlation revealed that participants with more autistic traits in *social communication* performed worse in self-recognition for simple actions.

Figure 6. Relations between AQ social communication subscale scores and self-recognition for simple actions. Note that higher AQ score indicates more autistic traits.

For complex actions, the stepwise regression analysis selected a model with three SPQ subscale scores as predictor variables (including *unusual perceptual experiences*, *odd behavior*, *ideas of reference* and *no close friends*) in relation to self-recognition performance. But the selected model did not reach statistical significance ($F(3,94) = 2.283, p = 0.084$). Upon further examination, we noticed a nonlinear quadratic relationship between SPQ *unusual perceptual experience* scores and self-recognition for complex actions. Thus, we introduced an additional predictor variable of quadratic SPQ subscale scores of *unusual perceptual experiences* to the stepwise regression analysis. The results converged to a significant model with two predictor variables (SPQ *unusual perceptual experience* subscale scores, and its quadratic term) $F(2,95) = 5.782, p = 0.004$. As shown in Figure 7, there was a significant relationship between the SPQ *unusual perceptual experiences* subscale and self-recognition performance for complex actions (spearman $\rho = 0.264$, 95% CI [.064, .445], $p = .008$). In addition to the linear relation, self-recognition performance for complex actions also related to a quadratic trend of SPQ *unusual perceptual* scores, revealed by significant coefficients to the quadratic term ($t(92) = -2.937, p = .004$). The coexistence

of linear and quadratic relations indicates that participants with mid-range SPQ *unusual perceptual experiences* scores showed best self-recognition performance for complex actions.

Figure 7. Relations between SPQ unusual perceptual experience subscale scores and self-recognition for complex actions. Note that higher SPQ scores indicate more schizotypal traits.

For imitation actions, the stepwise regression analysis selected a model with six predictor variables, including AQ *social communication* and *attention* subscale scores, three SPQ scores of *odd speech*, *suspiciousness*, and *no close friends*, and VMIQ-2 Kinesthetic scores, in relation to self-recognition performance ($F(6,91) = 2.895, p = 0.013$). However, only AQ *social communication* and SPQ *suspiciousness* scores showed significant coefficients ($t(90) = -3.286, p = .001$; $t(90) = -2.336, p = .022$). The follow-up nonparametric correlation analysis did not reveal significant relation between self-recognition performance and SPQ *suspiciousness* scores ($p = .263$), but confirmed its significant relation with the AQ *social communication* subscale scores (spearman $\rho = -0.229$, 95% CI $[-0.414, -0.026]$, $p = .023$). This result suggests that people with higher AQ traits associated with social communication ability performed worse in the self-recognition task for imitation actions. As self-recognition performance with imitation actions also correlated with the VMIQ-2 composite scores of motor imagery ability as reported

early, we ran a second stepwise regression analysis with four prediction variables, including AQ *social communication* scores and three VMIQ-2 subscale scores. This stepwise regression selected a model with two predictor variables, AQ *social communication* scores and VMIQ-2 kinesthetic motor imagery scores ($F(2,95) = 3.652, p = .030$). The follow-up nonparametric correlations confirmed the significant relations between self-recognition performance with AQ *social communication* and kinesthetic VMIQ-2 scores (spearman $\rho = -0.229, 95\% \text{ CI } [-0.406, -0.017], p = .029$) as shown in Figure 8.

We further examined how autistic traits and motor imagery abilities jointly impact the self-recognition performance. A moderation analysis revealed that the negative relationship between AQ *social communication* scores with self-recognition performance for imitation actions was moderated by kinesthetic motor imagery ability ($\beta = -0.032, 95\% \text{ CI } [-0.061, -0.003], p = .028$): more AQ *social communication* traits attenuated self-recognition performance, only when kinesthetic motor imagery ability was weakened (-1 *SD* low: $\beta = -.002, 95\% \text{ CI } [-0.045, 0.042]$; or average: $\beta = 0.033, 95\% \text{ CI } [-0.065, -0.003], p = .031$). Higher kinesthetic motor imagery ability (+ 1 *SD*) appeared to provide a compensatory effect, and mitigate the negative impact of high AQ *social communication* traits on self-recognition performance with imitation actions ($\beta = -0.066, 95\% \text{ CI } [-0.106, -0.025], p = .002$).

Figure 8. Relations between self-recognition for imitation actions with AQ *social communication* subscale scores (left panel) and with kinesthetic motor imagery ability (right panel). Note that higher AQ scores indicate more schizotypal traits, and higher VMIQ-K scores indicate weaker imagery ability.

Discussion

On a large sample of participants, we measured the impact of intrinsic traits and extrinsic action factors on self-recognition. Here, we not only replicated previous findings that humans can recognize their own actions in point-light displays (Burling et al., 2019; Loula et al., 2005; Cutting & Kozlowski, 1977; Prasad and Shiffrar, 2009), but importantly – extended the literature to introduce novel interactions between intrinsic factors (participant traits linked to motor simulation and subclinical sensorimotor processing: ASC and SSC) and extrinsic factors based on the action types (motor planning, action orientation and perceptual variability). The pattern of results further revealed hidden variance within subclinical traits. Specifically, the AQ social communication and SPQ unusual perceptual experiences subscales related to distinct extrinsic action types in self-recognition performance.

Extrinsic variability modulates self-recognition performance

First, we found that self-recognition performance varied according to the degree of motor planning, delineated by our extrinsic factor of action type (simple, complex, and imitation). A few prior studies have focused on item-level delineations based on perceptual variability or idiosyncrasies (e.g., Loula et al., 2005). However, the perceptual consequences of self-actions are generated from privileged access of one's motor plan during action performance (Knoblich and Prinz, 2001), and hence causally vary as a function of the degree of motor planning (e.g., Li et al., 2020). Complex actions required the greatest degree of motor planning due to the more complex variability of the goal representation space (relative to simple actions) (e.g., Li et al., 2020), and imitation actions required the least motor planning due to mimicry of movement patterns (Zimmer & Engelkamp, 1996; Schwartz & Plass, 2014). The performance pattern mostly mapped onto the motor planning differences, with greatest self-recognition performance for complex actions as compared to simple or imitation actions. However, we found no performance difference between simple (simple actions with semantic label; i.e., greater motor planning) and imitation (without semantic label; i.e., reduced motor planning) actions. Although reduced memory recall for

imitated action labels in comparison to self-generated actions has previously been shown, and attributed to lessened motor planning (see enactment effect; Zimmer and Engelkamp, 1996), the different outcome measures in our task—visual recognition versus enactment (memory recall for actions)—make it difficult to draw conclusive parallels. Recently, a similar study to ours used recognition of point-light actions as the outcome measure (Bläsing and Sauzet, 2018) and also found comparable performance for both imitated and self-generated dancing sequences of unfamiliar actions, significantly greater than the action observation condition. Hence, it is likely that the reduced variability of simple actions degraded the familiarity of the actions, reflected in lower performance than complex actions and comparable performance to imitation actions.

What mechanisms underlie self-recognition across action types? Prior work has speculated on two main contributors to self-recognition of actions. First, proprioceptive and kinesthetic information retained from executing familiar motor actions (i.e., motor experience) may principally modulate self-action recognition. On the other hand, participants may recognize their movements on the basis of idiosyncratic visual cues, measured via perceptual variability (i.e., speed of movements; motion trajectories in observed actions). For simple and complex actions, quantitative similarity analyses on both individual actions and individual participants revealed no significant relationship between perceived movement variance and self-recognition accuracy, but showed greater variability in complex than simple actions. For imitation actions, analysis of the visual recognition task showed significantly lower (i.e., chance) performance for recognition of briefly observed visual actions (actor-generated) as compared to self-generated actions. Across all action types, the self-recognition task further demonstrated the viewpoint-invariance (frontal and right/left half-profile) of identifying own actions, regardless of the degree of motor planning, confirming prior findings (Jokisch, Daüm, and Troje, 2006). Together, these findings underscore the importance of the motor system to self-recognition: perceptual experience does not appear to suffice for self-recognition. In keeping with common coding theory, actions signaling a closer match between the

motor system and perception (i.e., self-generated) enhance action recognition more so than those distally matched (i.e., other-generated) (Prinz, 1997).

Intrinsic interactions with extrinsic factors influence self-recognition performance

Our analyses revealed distinct interactions between the extrinsic factor of action types and intrinsic traits, linked to motor imagery ability and clinical subscales (AQ social communication, and SPQ unusual perceptual experiences). For imitation actions, both composite motor imagery ability and the kinesthetic subtype were significantly correlated with self-recognition performance. Motor simulation theories (Jeannerod 2001; Jeannerod and Pacherie, 2004) posit the central role of motor imagery during action perception. Our results suggest that a compensatory increase in motor imagery ability may be required to self-identify one's own imitation action, which consisted of the least amount of motor planning since no explicit action label was provided during the action execution session. No significant relationships were found between the visual imagery subtypes (internal and external) and self-recognition for any action types. This behavioral dissociation between visual and kinesthetic imagery neatly converges with neural evidence revealing partially distinct brain regions for visual imagery (parieto-occipital) and kinesthetic imagery (i.e., parietal and premotor) (Guillot et al., 2009). It is likely that during the perception of one's own action, motor expertise of own actions makes use of particular neural resources linked to kinesthetic motor imagery (e.g., Wei and Luo, 2010; Kim et al., 2011).

We also found negative relationships between the AQ social communication subscale and self-recognition performance for simple and imitation actions, but not for complex actions. This negative relationship was moderated by kinesthetic motor imagery traits: greater AQ social communication traits attenuated self-recognition performance for imitation actions, only when kinesthetic motor imagery ability was weakened (low or average). In other words, higher kinesthetic motor imagery ability appeared to mitigate the AQ social communication self-action performance difference. As motor

imagery is presumed to share neural resources with biological motion perception (e.g., Grèzes and Decety 2001) the negative AQ social communication relation may be driven by difficulties in biological motion processing, consistent with reduced brain activity in prefrontal and left temporal cortices in high AQ social communication individuals when viewing point-light actions (Puglia and Morris, 2017). This interpretation dovetails a recent behavioral study linking the AQ social communication subscale to atypical processing of local kinematic information in biological motion (Wang et al., 2018). For simple actions with less perceptual variability, superior local processing may be necessary to discriminate fine details of self from other actions, possibly compromised in those with high AQ social communication traits. By consequence, the nonsignificant relationship between AQ social communication and complex actions may result from the increased perceptual variability in the actions resulting from individualized body movements, providing a compensatory strategy to self-recognition, regardless of the AQ spectrum. Notably, the interpretation of weakened local processing in high AQ social communication traits is in contrast to behavioral patterns observed in biological motion research that utilize the composite AQ measure. Many of these studies show the reverse pattern—superior local processing and a generalized disturbance in global processing in high AQ individuals. However, findings from these studies remain inconsistent (largely attributed to task-specific variability) (e.g., van Boxtel et al., 2017) and a possible reconciliation could be obtained through exploration of the subscales, rather than on the aggregate measures.

Scores on SPQ unusual perceptual experiences were quadratically related to complex actions, such that low and high individuals performed worse at self-recognizing complex action sequences. How might the intrinsic SPQ subscale modulate performance on complex actions? Prior work suggests impaired action perception across the schizophrenia spectrum (Kim et al., 2005, Kim et al., 2011). However, we only observed a significant trend with self-recognition performance on one action type (i.e., complex actions). Thus, the present results cannot be reduced to a generalized abnormality in

biological motion perception. Rather, atypical action monitoring in suppressing the sensory consequences of action may produce false positives — misattributions that the action is externally generated (Frith et al., 2000). The unusual perceptual subscale focuses on the positive (i.e., first-rank symptoms) of SSC, including incoherent perceptual experiences that reduce one's sense of agency (Asai et al., 2008), blurring the boundaries between the self and other (e.g., Waters & Badcock, 2010; Postmes et al., 2014). In relation to atypical action monitoring, prior studies have shown that individuals high in SPQ unusual perceptual traits are more successful at self-induced tickling (i.e., Lemaitre, Luyat, & Lafargue, 2016), likened to a disrupted match between predicted efference copies and sensorimotor outcomes; see forward model accounts (Wolpert and Miall, 1996; Postmes et al., 2014). The action monitoring atypicality may be particularly exacerbated by complex actions that require a greater degree of motor planning and preparation. Weakened self-recognition performance on complex actions with those low on SPQ unusual perceptual experiences traits is less clear. A likely possibility may be due to decreased perceptual acuity in discerning subtle movement patterns, induced by the distraction of perceptual variance in complex action sequences. This could manifest in behavioral differences based on false negatives (i.e., decreased discrimination of perceptual idiosyncrasies), rather than false positives (i.e., misattributions).

Neither composite subclinical measure (schizotypal or autistic) showed a relation to self-recognition performance. If our analysis was restricted to the composite measures, this would suggest that physical aspects of the self (e.g., bodily recognition) are intact in both conditions, consistent with many studies on visual self-recognition (e.g., Ferrari & Matthews, 1983; Uddin et al., 2008; Dunphy-Lelii & Wellman, 2012; Gillespie-Smith et al., 2014; Lee et al., 2007; cf. Chakraborty and Chakrabarti, 2015). However, the clear pattern of relations with the subscales suggests that a focus on the composite measure can be misleading, as it masks the psychopathological variance in the general population. SSC and ASC have heterogenous socio-cognitive symptomatology, residing on a continuum that extends well

into the general population, and frequently updated in light of DSM revisions. While models of AQ and SPQ symptomatology posit the large phenotypic overlap between AQ and SPQ subscales (which our results similarly maintain), the AQ social communication and SPQ unusual perceptual experiences dimensions appear to reside on a diametric axis, largely exempt from the overlap (Dinsdale et al 2013; Ford and Crewther, 2014). The present results confirm the diametric relation presented in the prior work, as we found no relationship between the subdimensions of interest (i.e., AQ social communication and SPQ unusual perceptual experiences), which shared unique variance with each respective clinical composite measure. Since the composite measures average across the spectrum, a foundational approach for future individual difference studies should prioritize subscale parcellations, which may reveal finer-grained individual variability.

Our study presents some outstanding limitations. Though we separated actions based on motor planning, our actions included a range of social and non-social actions. In doing so, we preserved the naturalistic nature of the actions; however, additional studies can more specifically isolate the contribution of controlled action types. Another limitation pertained to the movement similarity analysis. Participants may have used different limbs to perform some actions, which may artificially inflate the dissimilarity. Additionally, subtle movement differences, not capturable with dynamic time warping analysis across groups, may also be needed to see whether motor performance differences are associated with psychometrically assessed ASC and schizotypal traits (e.g., Walker et al., 1999; Lenzenweger & Maher, 2002). Other quantitative metrics of variability (e.g., Coste et al., 2020) on these action types would also be beneficial, while out of scope for the present paper.

Few species are capable of self-recognition and develop motor-based, self-other mapping mechanisms in the brain (i.e., the mirror neuron system). Visual self-recognition of point-light actions provides a unique lens to gauge the core perceptual and motor mechanisms underlying self-representations in humans. These paradigms control for the level of visual familiarity people have with

self-related stimuli (e.g., compared to familiar faces, body images, voices) from a third-person perspective, highlighting the importance of “acting” in “seeing” the self. Our findings thus complement a diverse body of literature in self-processing, demonstrating that self-recognition is possible for stimuli even with little visual experience. Furthermore, the approach of studying individual differences provides new evidence for *how* the motor system may contribute to self-recognition— distinct aspects of motor processing tap into intrinsic and extrinsic routes, imbuing the core of self-awareness.

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Open Practices

This study was not preregistered.

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