Action plan diversity in children during control exploration: Link between action and sense of agency

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Abstract

The sense of agency refers to the subjective feeling of controlling one's own actions and, through them, external events. It is a crucial aspect of consciousness, indicating that an agent can understand the causal relationship between their actions and environmental changes and, more importantly, voluntarily influence the environment through their actions. There has been extensive debate about when children and which animals possess the sense of agency, primarily because they cannot easily report it. Observing actions might be a promising way to estimate the sense of agency without relying on introspection. However, despite actions containing rich information about human subjective feelings, there are very few ways to abstract such information. In the present study, we aim to clarify the relationship between actions and the sense of agency during control exploration using a dataset of 167 children (6-16 years old) acquired by Nobusako et al. (2022). We employ action plan analysis developed by Chang et al. (2024) to analyze motion sequences data which was self-generated by participants during a control detection task. The action plan analysis uses transformer-LSTM-based autoencoders to capture high-level, abstract representations of sequences of motor commands (referred to as action plans). This approach allows us to quantify action plan diversity that reflects control exploration behaviors. The results showed that action plan diversity can be a promising way to measure the sense of agency both within individuals and among them. This suggests that simply observing how actions change under different control conditions can quantitatively reflect the emergence of the sense of agency in children. The findings and methodology provide a highly novel and useful tool for studying the sense of agency in broader populations and species in future studies.

Keywords: sense of agency, action plan, causal relationship, deep learning, active inference.

Introduction

Volition is a crucial aspect of consciousness. How and when do we decide to act? There is no doubt that neural activities in our brain generate and initiate voluntary intentions. However, the gap between physical neural activities and abstract volitions remains largely unresolved (Frith, 2013; Haggard, 2008, 2019; Schurger et al., 2012). Computational approaches have been used to understand human behavior and volition. For example, the free energy theory suggests that human behaviors are driven to minimize ambiguity in the environment (Friston et al., 2016; Picard & Friston, 2014). Learning the causal relationships in the environment, especially between one's own actions and events in the external world, is essential for humans to establish the sense of "self" and optimize their behaviors when interacting with the environment. The subjective feeling of being able to voluntarily control one's own actions, and through them, control external events, is called the sense of agency. There is evidence that humans start to learn the causal relationship between their actions and sensory consequences from a very early stage of development. For example, as early as 10 weeks old, infants show increased frequency of foot thrusts when a cord is looped around their ankle and hooked to an overhead mobile, compared to when the mobile is moved similarly by the experimenter instead of the cord (Rovee & Rovee, 1969). This well-known phenomenon has been widely used to study how infants acquire the sense of self through actions (Rochat & Striano, 2000; Sloan et al., 2023; Thelen et al., 1987; Watanabe & Taga, 2011).

The sense of agency is largely examined in human adults because they possess well-established introspective abilities to provide subjective reports, as well as perform implicit measures tasks such as intentional binding and sensory attenuation (Wen & Imamizu, 2022). It is more challenging to study the sense of agency in younger populations, such as infants and children. Many previous studies attempted to observe changes in infants' behaviors when their movements produce conjugate sensory feedbacks to infer if they can learn about their control in the environment (Rochat & Striano, 1999; Rovee-collier et al., 1978; Rovee & Rovee, 1969). However, there is a lack of solid evidence linking these simple behavioral pattern changes with the sense of agency (Zaadnoordijk et al., 2018). Actions contain rich information regarding one's intentions and cognitive processes. However, traditional methods of action analysis fail to abstract such information efficiently.

A recent study reveal a new understanding of the sense of agency, emphasizing that this sense arises not merely from sensory feedback but from actively formed informative action policies (Chang et al., 2024). Notably, individuals form high-level, low-dimensional “action plans” that represent sequences of actions to infer their degree of control over environmental changes. Utilizing deep learning techniques, particularly transformer-LSTM-based autoencoders, researchers have successfully captured these action plans. This innovative approach reveals the geometrical and dynamical properties of these plans, which accurately predict individuals’ behavioral responses in agency tasks. In contrast to previous research focusing on oversimplified aspects of behavior such as movement frequency, speed, and repetition ratios, this study offers a more sophisticated method by capturing an internal representation of action policies. These policies non-linearly generate the complex high-dimensional motor sequences that inform our sense of agency. Therefore, this method is a promising approach to uncovering the link between actions and the sense of agency.

In the original study conducted by Chang et al. (2024), the dimensionality of action plans was calculated to quantify action plan diversity. The study reported that patients with schizophrenia exhibited lower action plan diversity and, more importantly, their action plan diversity did not vary with the actual level of control, compared to healthy controls (Chang et al., 2024). This finding aligns with reports that patients with schizophrenia show an impaired sense of agency (Bühler et al., 2016; Garbarini et al., 2016; Maeda et al., 2012, 2013; Moore, 2016; Moore & Fletcher, 2012; Tan et al., 2023; Zito et al., 2020). Therefore, action plan diversity may be a valuable indicator for revealing the relationship between actions and the sense of agency.

In the present study, we acquired a dataset of 167 children aged 6-16 years, focusing on their finger movements on a touchpad and their task performance in detecting control over multiple moving objects from a previous study (Nobusako et al., 2022). In the experimental task, children were asked to move their index finger on a touchpad to trigger the motion of three dots on the screen. The onset, offset, and moving speed of the three dots were identical and corresponded to the finger movements. However, the moving directions of the three dots were different. Only one target dot reflected 0%, 20%, 40%, 50%, 60%, 80%, or 100% of the finger movements (see Wen et al., 2020 for the details of motion combination algorithm). The other two dots moved along pre-recorded trajectories. After moving for up to 10 seconds, children were asked to identify the target dot they felt was (partially) controlled by their finger movements. The detection accuracy of the target dot was used as a measure of the sense of agency (Wen & Imamizu, 2022). The original study reported that the detection accuracy in the 5-6-year-old group was significantly worse compared to older groups, and there was a negative correlation between detection threshold and age among all participants ($r = -0.358$, $p < 0.001$) (Nobusako et al., 2022). This study was the first to examine the sense of agency during continuous movements in school-age children. However, a limitation of this task is that it requires attentional control over the three dots: either paying attention to all of them simultaneously or switching attention among them. Although this limitation can be mitigated by allowing sufficient time for exploration, it is still difficult to eliminate completely. We suggest that by conducting action analyses, it is possible to observe the sense of agency through actions while avoiding the potential influence of other cognitive functions, such as attention.

The current study aims to examine whether action diversity in children changes depending on their actual level of control, and whether this diversity is linked to individual sensitivity of the sense of agency. We trained a model employing a transformer-LSTM-based autoencoder for each child using their finger movements, ensuring that the model could accurately restore the trajectories from a low-dimensional action space (see Methods and Chang et al., 2024 for details of the model). The action plan diversity was calculated for each trial, and we examined the relationship between action plan diversity indices and control detection accuracy, as well as the relationship between action plan diversity indices and age.

Results

We trained an individual model for each participant to better capture how their action plans change depending on the experimental conditions. Additionally, the results using a single model for all participants are included in Supplementary Materials S1. These results are similar to those obtained using individual models. Training with individual models is considered more effective in capturing how action plans change depending on the actual level of control within each individual.

First, the action plan diversity was calculated for each trial and each individual, then averaged for each condition. Similar to the detection accuracy (Figure 1A), the action plan diversity increased with the level of actual control (Figure 1B). The increased action plan diversities in higher control conditions revealed active inference behaviors that attempt to accumulate more causal evidence to support the sensed control (Chang et al., 2024). The repeated-measures ANOVA revealed a significant main effect of control on action plan diversity ($F(6, 798) = 16.067$, $p < .001$, partial $\eta^2 = 0.108$). The action plan diversity in the 50% control condition was significantly higher than those in the 0%, 20%, and 40% control conditions ($t(161) = 3.647$, $p < .001$; $t(161) = 3.686$, $p < .001$, $t(160) = 3.227$, $p < .002$, respectively, with a Bonferroni adjusted significance level of .008 for six comparisons between the 50% control condition and other control conditions), and was significantly lower than those in the 60% and 100% control conditions ($t(158) = 2.994$, $p = .003$; $t(142) = 3.012$, $p < .003$, respectively). The df values varied because some participants lacked trials longer than 5 seconds in some conditions (see Methods for a detailed description of data exclusion). The difference between the 50% and 80% control conditions did not reach significance ($t(144) = 2.221$, $p = .028$). In short, the results showed that action plan diversity is a good indicator of the sense of agency across different control conditions.

Next, we examined whether action plan diversities can be used as an indicator to measure individual differences in the sense of agency. This is important because subjective reports of the sense of agency lack the ability to distinguish between criteria of judgment and sensitivity to control (Wen et al., 2024) , making them unsuitable for comparisons among individuals. Figure 2A shows the plot of individual detection accuracy (average across all trials) against individual action plan diversity. Surprisingly, control detection accuracy was significantly negatively correlated with average action plan diversity ($r = -.491$, $p < .001$). This was not observed in the previous study with a small sample size of patients and healthy controls (n = 25 in each group) by Chang et al. (2024). It is possible that as children's sensitivity of the sense of agency rapidly develops with age, they may be able to more effectively use less diverse action plans to detect the target dots.

Furthermore, to examine how participants change their active plans depending on the actual level of control., we applied a linear regression of action plan diversity against the actual level of control for each individual and calculated the slope as the *action* *plan sensitivity*. We observed a significant positive correlation between control detection accuracy and action plan sensitivity ($r = .268$, $p < .001$). This indicates that children with a more sensitive sense of agency changed their action plans more extensively according to the actual level of control. These findings suggest that, instead of the absolute value of action plan diversity—which can be affected by subjective task difficulty—action plan sensitivity, which reflects how sensitively individuals vary their actions according to control, is a good indicator of individual sensitivity to the sense of agency.

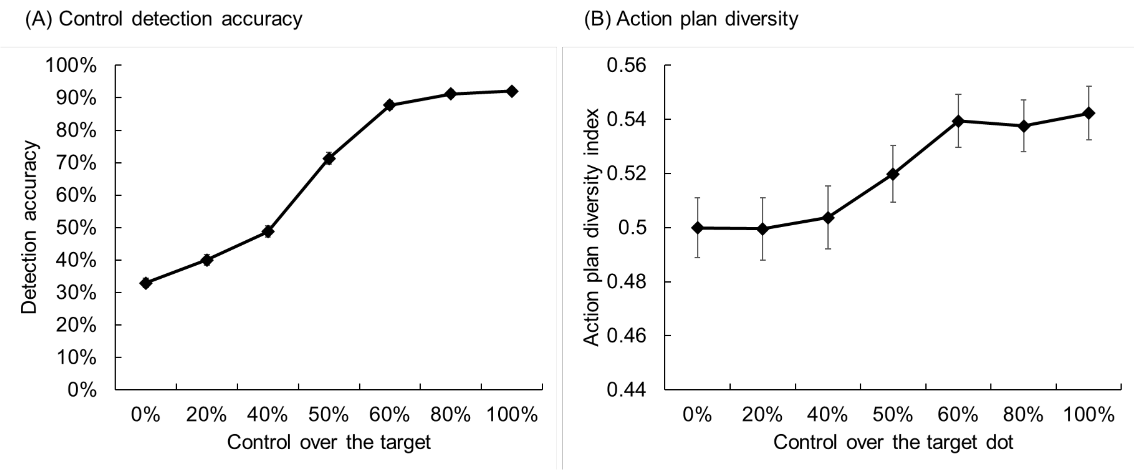

Figure 1. The control detection accuracy (A) calculated from the original dataset and the action plan diversity (B) calculated from the trained models. Both indices showed a clear effect of the actual level of control over the target, indicating their utility as an index of the sense of agency. Error bars represent standard errors.

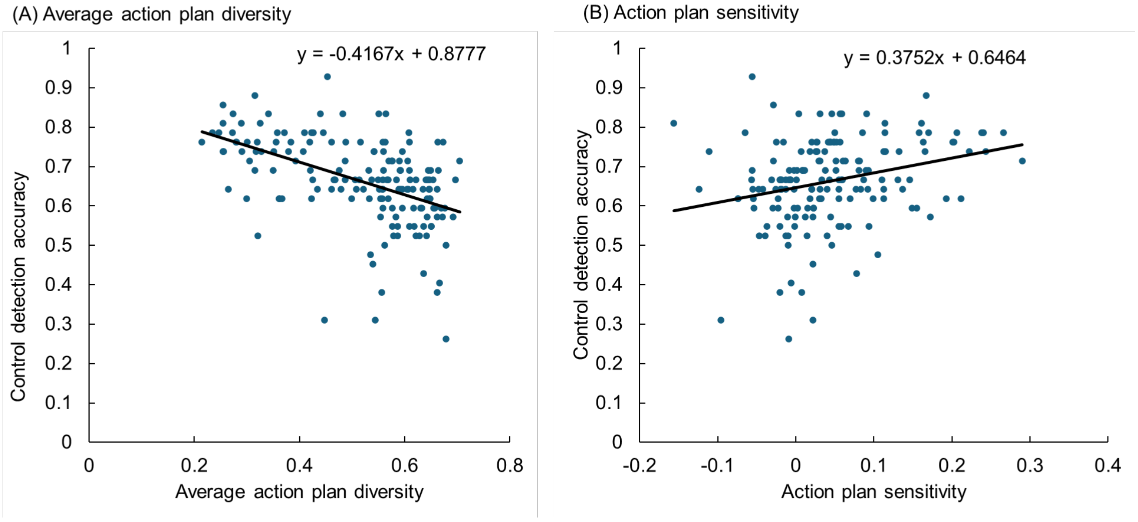

Figure 2. The plot of control detection accuracy against average action plan diversity (A) and the plot of control detection accuracy against action plan sensitivity (B) for all individuals.

Discussion

The present study utilized transformer-LSTM-based autoencoders proposed by Chang et al. (2024) to capture lower-dimensional action representation from high-dimensional motion data for a dataset of 167 school-age children conducting a control detection task acquired by Nobusako et al. (2022). We aimed to use indices abstracted purely from actions to evaluate the sense of agency in children, avoiding potential influences from factors such as reporting bias and attentional allocation abilities. First, the action plan diversity showed a clear sigmoid-like function of control, indicating that actions indeed contain rich information regarding the sense of agency and that action plan diversity is a good indicator of the sense of agency across different control conditions. Next, we examined both the average action plan diversity and action plan sensitivity among individuals and found that the latter is a promising indicator of individual sensitivity to the sense of agency. Since action plan sensitivity is measured purely based on actions (i.e., moving trajectories), it can be applied to younger populations and even animal studies where subjective reporting is difficult.

The index of action plan diversity is mathematically a measure of the dimensionality of one's action plan samples in the action plan space. In other words, it reflects the complexity of one's action plans and how often people change their action patterns. The original study showed that the compressed action plan space could accurately predict individuals' agency judgments and control detection accuracy by combining the information of sensory input (i.e., the trajectory of the dot movement on the screen). Furthermore, it was reported that action plan diversity is sensitive to the actual level of control in healthy controls but not in patients with schizophrenia, revealing the normal and abnormal relationships between actions and the sense of agency in the two groups, respectively. The present study acquired a much larger sample and replicated this finding, further demonstrating the usability of action plan diversity as a measure of the sense of agency through actions. More importantly, we found that action plan sensitivity, rather than the absolute value of action plan diversity, is a good measure of individual sensitivity to the sense of agency. A person with a more sensitive sense of agency can better distinguish between events/objects they can control and those they cannot control (Wen et al., 2024). Such a person can usually identify the target dot more accurately in the control detection task (Wen et al., 2018, 2020). However, this control detection may be difficult for people who have difficulty switching their attention among dots or making decisions. Chang et al. (2024) showed that the relationship between action plan diversity and control was observed not only when participants explored their control among three dots but also when participants interacted with only one dot. Therefore, analyzing the actions when participants interact with a controllable object under different levels of control can reveal the sense of agency even when they cannot report it. This method can potentially be applied to other types of actions, such as body movements and eye movements, and therefore can be used to examine the sense of agency in broader populations and even in animals.

Lastly, the present study examined how action plan diversity reflects both the sense of agency within each individual under different control conditions and the sense of agency among individuals aged 6-16 years. The variance in the sense of agency within this age group is significant. The method of using control detection accuracy, as employed in the original study by Nobusako et al. (2022), may be influenced by better attention allocation in older children, which develops gradually in school-age children (Dye & Bavelier, 2010; Hagen & Hale, 1973). Our study suggests that action plan diversity may serve as an alternative means to observe the sense of agency in children while minimizing the possible influence of other cognitive functions, such as attention. It is also reported that the sense of agency changes throughout the lifespan. For example, a study reported that the illusion of vicarious agency—in which people attribute an experimenter's gestures to their own when the experimenter sits behind participants and puts her hand forward, making it appear like the participants' hand—was less pronounced in older adults (Cioffi et al., 2017; Metcalfe et al., 2010). However, this can be due to either the sensitivity of distinguishing between self and other or the criterion of rating (Wen et al., 2024). It is worth examining how people vary their action plans according to control in both younger and older populations to further understand how the sense of agency changes throughout the lifespan.

Methods

Dataset

The dataset was directly acquired from the corresponding author of the previous study by Nobusako et al. (2022). All participants' individual information was anonymized, and data sharing was conducted with the approval of the local ethics committee of the original research institute. The original paper contained 200 valid samples. However, due to an equipment failure, only 167 samples were recovered from the broken hard disk and were shared with the authors of the present study.

The original dataset was acquired by four experimenters in different locations (e.g., schools). Children moved their index fingers on a touchpad and then orally reported the number of the target dot. The experimenters recorded the answers by typing them on a keyboard. The maximum trial length was 10 seconds; however, the experimenters could terminate a trial if the child orally reported the target dot before reaching the end, resulting in some trials being shorter than 10 seconds (33.5% of all trials). We used a sliding window of 1 second (i.e., 60 frames) during the training of the motions. Trials shorter than 1 second were excluded from training. Four participants were excluded because they did not have sufficient trials for training. After training, we calculated the index of action plan diversity for the first 5 seconds of each trial to avoid the possible effect of trial length on action plan diversities. Trials shorter than 5 seconds but longer than 1 second were used for training but excluded from the calculation of action plan diversity (19.9% of the trials). Another participant was excluded from the statistical analysis of action plan diversity due to a lack of trials with higher than 50% control. Many of the excluded trials were those with higher levels of control over the target because they were easier for the children to identify, resulting in shorter trials. This exclusion may affect the action plan diversity of higher control level conditions. However, a 5-second trial length ensures a reliable calculation of action plan diversity and facilitates comparison with the previous study conducted by Chang et al. (2024).

Model training and analysis

The procedure of model training was identical to the study by Chang et al. (2024). The transformer-LSTM-based autoencoder contained a transformer-based encoder, a bottleneck, and an LSTM-based decoder (see the original paper for details of the model's architecture). A motor sequence of 60 frames (i.e., 1 second) was fed to the model and mapped to an action plan space (i.e., the bottleneck). The action plan space contained 16 dimensions to capture the essential features of the motor sequence. A sliding window of 60 frames, moved by 1 frame each time, was applied to each trial for model training. After completing the training, the decoder takes the first time point of each motor sequence as input to reconstruct the original motor sequence. Figure 4 shows some examples of the original and reconstructed motor sequences. As shown in these examples, the action plan space was able to capture the essential features of the action plan for each individual in a lower-dimensional space (i.e., 16 dimensions).

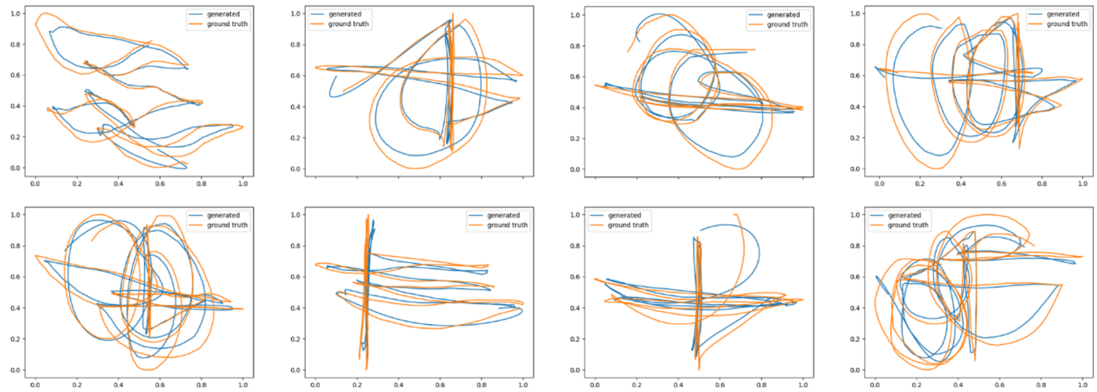

Figure 4. Examples of participants' moving trajectories (i.e., ground truth, yellow lines) and model-generated (reconstructed) trajectories (blue lines). The model was able to capture the essential features of each motion.

After model training for each participant, we conducted a dimensionality analysis to calculate the index of action plan diversity for each trial. The motor sequence of each trial was mapped into the 16-dimensional action space. We performed Principal Component Analysis (PCA) on these data points within the action space and obtained the distribution of component contributions. An exponential curve was then fitted to this distribution, and the rate parameter λ was determined. If the dimensionality of the action space is low, a few principal components would be sufficient to represent the variance of the data points in the action space, resulting in a relatively large λ. Therefore, the index of action plan diversity was calculated as $(1 - \lambda)$ (Chang et al., 2024).

To test whether the action plan diversity is closely linked with the sense of agency, we first conducted a repeated-measures ANOVA on the averaged action plan diversity with the within-participant factor being the level of control over the target dot (0%, 20%, 40%, 50%, 60%, 80%, and 100%). For post-hoc comparisons, we compared the action plan diversity in the 50% control condition with the other conditions (i.e., six paired-sample comparisons). Bonferroni adjustment of the significance level was applied. Furthermore, we conducted a linear regression of action plan diversity depending on the actual level of control for each individual. The slope of the linear regression was named action plan sensitivity, referring to how sensitively individuals change their actions depending on the actual level of control. We then examined the correlation between the action plan indices (i.e., individual average action plan diversity and individual action plan sensitivity) and participants' control detection performance and their ages.

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Declaration of interests

The authors declare that no competing interests exist.

Author Contributions

WW: conceptualization, analysis, writing – original draft; HA: analysis, writing – review & editing; AC: conceptualization, analysis, writing – review & editing; JM: analysis, writing – review & editing; YS: conceptualization, writing - review & editing; YN: conceptualization, writing - review & editing; SN: conceptualization, data collection, writing - review & editing

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