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Hyperactive ADHD symptoms are associated with increased variability in thought content in less constrained contexts

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The current study used two complementary methods to examine whether hyperactive and inattentive ADHD symptoms are differentially linked to thought dynamics under contexts that differ in the extent to which constraints are placed on ongoing thoughts. First, participants voiced aloud their thoughts in real-time (i.e., Think Aloud task), under two conditions varying in the levels of constraints exerted on their thoughts. Individuals with more hyperactive symptoms displayed heightened variability in thought content only in the less constrained condition. Second, participants completed seven days of ecological momentary assessment during which they received six thought probes daily asking the extent to which their thoughts were freely moving (as a proxy for thought content variability) and a question that captured different levels of constraints. Hyperactive symptoms were positively associated with freely moving thoughts only during responses that corresponded with lower levels of constraints. Across two approaches, we provide converging evidence that hyperactive, but not inattentive, ADHD symptoms are associated with increased thought content variability during lower levels of deliberate constraints on thoughts. Together, these results support the Dynamic Framework of Spontaneous Thought and highlight the importance of considering context in the study of thought dynamics in ADHD.

Keywords Spontaneous thought, Thought dynamics, Mind wandering, ADHD, Think aloud, Ecological momentary assessment

The mind is in constant flux. Throughout the day, our mental experiences come and go; some fleeting, others sustained, some overstaying their welcome. The manner in which mental experiences fluctuate over time is referred to as thought dynamics, a topic of increasing interest considering its putative relationship with mental health and clinical conditions[1–3]. In particular, attention-deficit/hyperactivity disorder (ADHD) has been theoretically associated with increased variability in thought content over time[4]. Although ADHD is characterized by a heterogeneous symptom presentation encompassing hyperactivity as well as inattention[5], it is currently unknown whether the putative increased dynamics in thought content is equally driven by both these types of symptoms.

Ongoing thoughts have been mostly studied through the lens of the 'what' and 'when', that is, the content of thought and situations in which they arise, respectively[6,7]. Less consideration has been given to an equally important dimension of thoughts: the 'how', that is, the way thoughts rise and fall over time. In the Dynamic Framework of Spontaneous Thought, Christoff and colleagues[4] proposed that the dynamics of thoughts are influenced by different types of constraints on thoughts. One type of constraint is deliberate constraints, which are characterized by directing and sustaining attention with a subjective experience of volition (e.g., restricting one's thoughts to writing a manuscript). The degree of deliberate constraints influences the dynamics of thoughts, with high levels of deliberate constraints being linked to attention focused on a single topic whereas low levels of deliberate constraints being linked to increased variability in thought content (i.e., thoughts

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moving between loosely connected topics). Importantly, these authors proposed that altered patterns of thought dynamics are manifested in certain clinical conditions. Recent empirical evidence supporting some of their predictions demonstrated that ruminative tendencies, a common feature of depression[8], are associated with reduced variability in thought when participants were instructed to voice aloud whatever thoughts came to mind in real-time[3]. There is however still a paucity of empirical data related to other common clinical conditions such as ADHD that are associated with heightened thought variability, the other end of the extremes in thought dynamics.

ADHD is characterized by difficulty in controlling and sustaining attention. Hyperactive symptoms involve both physical and mental restlessness, with the latter being more common in adults[9–11], whereas inattentive symptoms relate to difficulty initiating and sustaining attention towards completion of a goal[12]. The Dynamic Framework of Spontaneous Thought hypothesizes that ADHD is characterized by high levels of variability in thought content resulting from decreased constraints on thoughts[4]. Although this framework does not dissociate between these two types of symptoms in their association with thought dynamics, it is possible that hyperactive symptoms may be more closely linked to heightened variability in thought content due to their association with mental restlessness as compared to inattentive symptoms[9–11,13]. Thus far, the majority of studies have examined a related thought dimension, thoughts that are unrelated to an ongoing task, revealing that higher levels of ADHD symptoms were associated with a higher propensity to experience task-unrelated thoughts across various contexts[10,14–18]. Interestingly, task-unrelated thoughts have been positively linked to variability in thought content[19–21], such that higher levels of variability in thought content occur during task-unrelated thoughts compared to thoughts focused on the ongoing task. Consistent with this finding in the general population, a couple of studies have found that the task-unrelated thoughts of individuals with ADHD, compared to controls, were more likely to display higher levels of variability in thought content[17,21].

Further support comes from studies that assessed related aspects of thought dynamics using questionnaires. A strong positive relationship has been reported between hyperactive and inattentive symptoms of ADHD and the propensity to experience (1) thoughts constantly on the go, (2) thoughts fleeting from one to another, and (3) multiple thoughts at the same time based on the Mind Excessively Wandering Scale[22,23]. On the other hand, Martz and colleagues[11] reported that only hyperactive, but not inattentive, symptoms of ADHD were positively related to participants' experience of having an excessive amount of thoughts happening very rapidly, characterized by items such as 'My thoughts keep changing topics' and 'There is a succession of thoughts in my mind, racing from one to the other with incredible ease', as captured by the Racing and Crowded Thoughts Questionnaire[24]. Although these findings shed light on the general relationship between ADHD and overall tendencies to experience aspects of thought dynamics, they were based on questionnaires that rely on retrospective recall, which are susceptible to memory inaccuracies. These questionnaires also rarely consider the influence of context on how thoughts dynamically unfold over time.

The role of context may be important, as individual differences in thought dynamics may not be uniform across time and situations in those with ADHD. This is exemplified by the finding that the experience of racing thoughts in ADHD increases throughout the day, as assessed by questions that retrospectively inquired about experiences of racing thoughts at different timepoints in the day[11]. The experience of thoughts that move freely from one topic to another, reflecting high levels of thought variability, has also been shown to ebb and flow throughout the day in the general population[25]. Importantly, the variability in thought content depends on whether these thoughts are related to the ongoing task[19], which serves as a proxy for deliberate constraints. The degree of deliberate constraints fluctuates depending on individual differences, transient fluctuations in internal states (e.g., mood, motivation, fatigue), and the characteristics of the tasks that punctuate our daily lives. For instance, the willingness to engage with homework varies widely from one student to another. At the same time, motivated students may occasionally find themselves unwilling to do their homework because they are tired or transiently unmotivated. Some tasks require sustained attention, reflecting high levels of deliberate constraints, because task performance is highly penalized by attentional lapses. In contrast, other tasks can be performed satisfactorily while one engages in a concomitant task such as engaging with one's inner thoughts. On the extreme end, we sometimes perform tasks demanding very little attention (e.g., commuting by train or taking a shower) or have no particular task to perform (e.g., idle time).

Such situations of minimal deliberate constraints are arguably best suited to observe individual differences in thought dynamics[4]. In ADHD, capturing thoughts occurring in such contexts where deliberate constraints are low may therefore be optimal to observe the predicted heightened thought dynamics. This would suggest that clinically relevant individual differences in thought dynamics may be more difficult to observe in contexts where deliberate constraints are more pronounced. Nevertheless, whether differences in thought dynamics can indeed only be observed in situations of low deliberate constraints, or whether subtle differences in thoughts dynamics may be observed even in tasks exerting higher levels of deliberate constraints given an appropriately sensitive test capturing thought dynamics, remains an open question. Developing a robust understanding of the metrics and circumstances that are optimal for assessing thought dynamics is important for accurately capturing this phenomenon.

A common method to study thoughts across contexts is ecological momentary assessment, in which participants are asked to report on their most recent thought. This method has valuable advantages, including high ecological validity as it assesses thoughts in daily life as well as circumventing the memory inaccuracies that are often associated with retrospective measures. However, it is limited by the self-report nature of its assessment of thought dynamics, which may be compromised in some populations. A method that complements ecological momentary assessment is the Think Aloud paradigm, which captures thought dynamics without relying on self-assessments. In recent years, many studies have used it to capture what people think about when they are not instructed to focus their attention on a task or particular topic for an extended period of time[3,26–29]. Past studies have revealed individual differences in thought dynamics predictive of personality traits (e.g., creativity[26]) and

mental health outcomes (e.g., brooding[3]). No studies to our knowledge have assessed thought dynamics using these two complementary naturalistic approaches and across different levels of deliberate constraints in ADHD.

The goal of the present study was to assess whether individuals with hyperactive and inattentive features of ADHD are associated with differential patterns of thought dynamics and, if so, whether such differences are equally detectable across contexts at different levels of deliberate constraints (see Fig. 1). Based on the Dynamic Framework of Spontaneous Thought and consistent with descriptions of thought processes in ADHD as "short-lived thoughts that flit from one thing to another or jump around between different ideas"[13] (p. 531), we predicted that both types of ADHD symptoms would be associated with heightened variability in thought content. However, as hyperactive symptoms have been shown to become internalized as mental restlessness in adulthood[9–11], which closely approximates the conceptualization of thought dynamics, we expect this tendency to be more strongly associated with hyperactive symptoms than with inattentive symptoms. Finally, we also expected these tendencies would be most pronounced during conditions reflecting lower levels of deliberate constraints. Given that ADHD symptoms are known to be normally distributed across the general population[30,31] and can impact mental functioning and attentional control even at subclinical levels[32],we did not restrict our sample to clinical ADHD cases but rather explored associations between trait-like dimensions of hyperactivity and inattention and thought variability.

This study addressed the above aims using two complementary methodological approaches implemented in two separate components. In the first component, we used two versions of the Think Aloud paradigm to capture thought content variability under different levels of deliberate constraints in a naturalistic setting. The first Think Aloud task had no prompt, reflecting lower levels of deliberate constraints, so as to maximize the opportunity to capture variability in thoughts content. The second Think Aloud task provided a prompt designed to increase deliberate constraints on thoughts. We anticipated that ADHD symptom severity would predict heightened variability in thought content on this task, operationalized as a tendency to have shorter thoughts transitioning abruptly and spanning numerous semantically unrelated topics, and that this tendency would be more pronounced for hyperactive symptoms and during the version with no prompts reflecting lower levels of deliberate constraints.

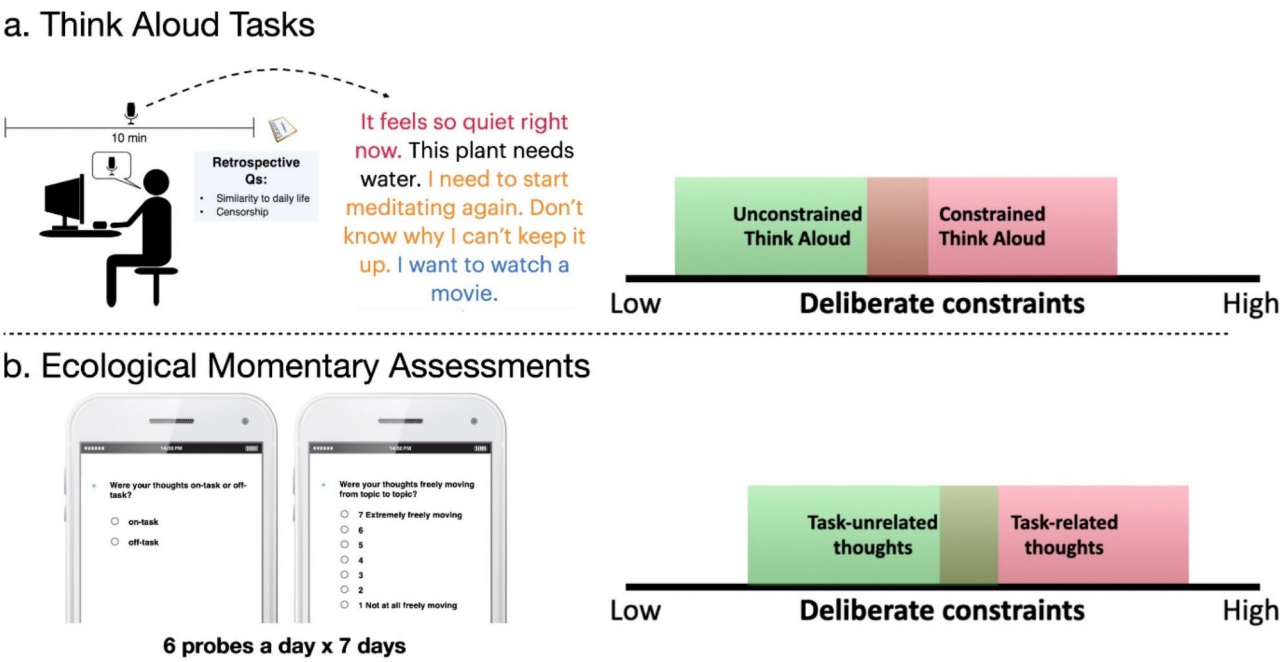

Fig. 1. Schematic and Conceptual Representations of the Tasks. (**a**) Study Component 1: Think Aloud task. The top left panel represents the Think Aloud paradigm. Participants were asked to voice aloud their thoughts in real-time either without a prompt (unconstrained Think Aloud) or with a prompt to think about family or friends (constrained Think Aloud). We present an example of one portion of a transcript, with each color indicating a separate thought. The top right panel illustrates the level of deliberate constraints associated with the two versions, with the unconstrained Think Aloud exerting lower levels of deliberate constraints compared to the constrained Think Aloud. (**b**) Study Component 2: Ecological momentary assessment. The bottom left panel represents the questions asked at each probe. Participants received 6 probes a day for 7 days asking them to report on the task-relatedness of their thoughts, as an index of levels of deliberate constraints, as well as the degree to which they were freely moving, as an index of thought variability. The bottom right panel illustrates the level of deliberate constraints associated with task-related and unintentional task-unrelated thoughts, with unintentional task-unrelated presumably exerting lower levels of deliberate constraints than task-related thoughts. Overall, it was hypothesized that thought dynamics would be more pronounced in situations of lower deliberate constraint (unconstrained Think Aloud and unintentional task-unrelated thoughts).

In the second component, we assessed whether the levels of hyperactive and inattentive symptoms modulated the experience of thought dynamics in daily life using ecological momentary assessment. The task-relatedness of thoughts was taken as a proxy for the level of deliberate constraints, with task-related thoughts reflecting relatively higher levels of deliberate constraints than task-unrelated thoughts. Similar to the first component, we predicted that hyperactive symptoms would be related to higher levels of heightened thought variability, characterized as freely moving thoughts, and that this tendency would be more pronounced for task-unrelated thoughts presumably reflecting lower levels of deliberate constraints. We anticipated that a similar pattern would be observed with inattentive symptoms, albeit to a lesser extent.

Results

Hyperactive, but not inattentive, ADHD symptoms are associated with heightened variability in thought content under lower deliberate constraints during the think aloud task

Hyperactive symptoms

We examined the levels of thought dynamics associated with hyperactive symptoms across the unconstrained and constrained conditions of Think Aloud conditions indexing lower and higher levels of deliberate constraints, respectively. A detailed report of the results of the following analyses are shown in Table 1; Fig. 2a. The interaction model predicting variability in thought content revealed a significant main effect of hyperactive symptoms ($p = .002$) but no main effect of condition ($p = .133$) nor an interaction effect ($p = .127$). A priori simple slope main effects analysis revealed that the positive slope of the relationship between hyperactive symptoms and variability in thought content was significant for the unconstrained Think Aloud condition ($p = .002$), indicating that higher levels of hyperactive symptoms were associated with higher levels of thought content variability. This was not the case for the constrained Think Aloud condition ($p = .322$).

We did not observe a relationship between hyperactive symptoms and associative transitions ($p = .647$) nor the total number of words generated ($p = .953$). These results are reported in the Supplementary Tables S1-S2.

Inattentive symptoms

The interaction model predicting variability in thought content did not reveal a main effect of inattentive symptoms ($p = .101$) nor condition ($p = .358$). The interaction was also not significant ($p = .348$). Planned simple main effects analysis revealed that neither of the simple slopes for constrained or unconstrained Think Aloud was significant (both p's > .101).

Neither of the interaction models predicting associative transitions and total number of words generated based on inattentive symptoms revealed significant main effects nor interactions (both p's > .450). These results are reported in the Table 1 and Supplementary Tables S3-S4.

Hyperactive, but not inattentive, ADHD symptoms are associated with greater thought dynamics under lower deliberate constraints as assessed with ecological momentary assessment

We examined the levels of thought dynamics in daily life as captured by ecological momentary assessments in individuals with symptoms of ADHD across different levels of deliberate constraints as indexed by task-relatedness. A detailed report of these results is shown in Table 2; Fig. 2b. There was no significant main effect of task-relatedness ($p = .553$) but the main effect of hyperactive symptoms was significant ($p = .002$). Crucially,

	Variability in Thought Content							
	Hyperactive symptoms				**Inattentive symptoms**			
Interaction model								
	b	**se**	***t***	***p***	***b***	**se**	***t***	***p***
Intercept	-2.53	0.81	-3.12	0.002	-1.09	0.68	-1.62	0.108
Level of symptoms	0.04	0.01	3.16	0.002	0.02	0.01	1.65	0.101
Condition	1.73	1.15	1.51	0.133	0.88	0.96	0.92	0.358
Interaction	− 0.03	0.02	-1.53	0.127	− 0.01	0.01	− 0.94	0.348
	$F(3,178) = 3.67$, $p = .014$, *adj.* $r^2 = 0.04$				$F(3,178) = 0.94$, $p = .422$, *adj.* $r^2 = 0.00$			
Simple slope analysis								
Think Aloud condition	***b***	**se**	***t***	***p***	***b***	**se**	***t***	***p***
Unconstrained	0.04	0.01	3.16	0.002	0.02	0.01	1.65	0.101
Constrained	0.01	0.01	0.99	0.322	0.00	0.01	0.32	0.750

Table 1. Interaction models predicting the variability in thought content factor by levels of ADHD symptoms and Think Aloud condition and their planned simple main effects analyses. Separate interaction models tested the interaction between ADHD symptoms (hyperactive or inattentive) and condition (unconstrained vs. constrained Think Aloud, indexing lower vs. higher levels of deliberate constraints, respectively). The reference variable for condition was unconstrained Think Aloud. Results of the planned simple slope analysis for examining the main effects of hyperactive symptoms on thought content variability for each Think Aloud condition are shown in Fig. 2A.

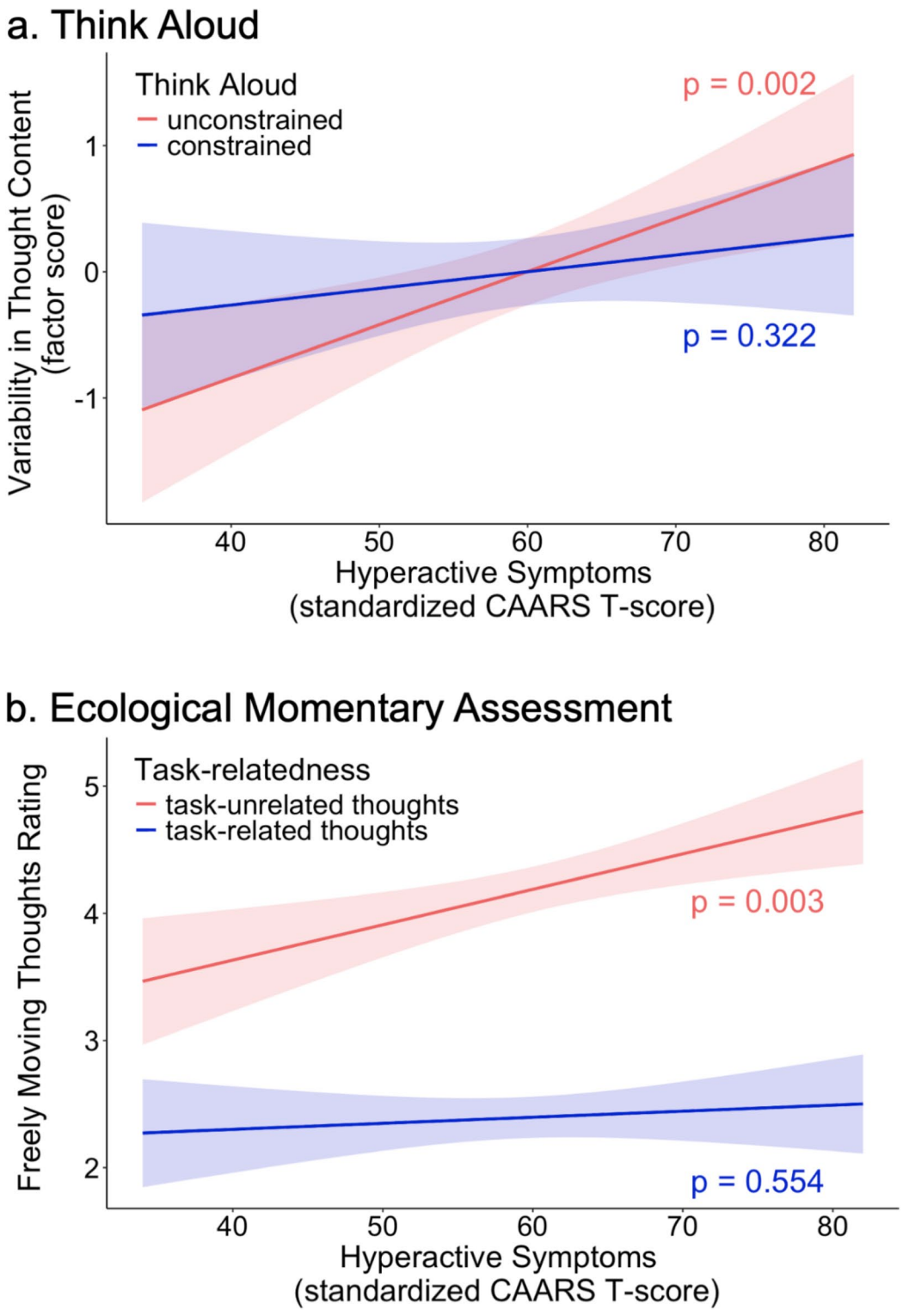

Fig. 2. Planned simple slope main effects analyses predicting variability in thought content based on hyperactive symptoms in the (**a**) Think Aloud and (**b**) Ecological Momentary Assessment components. Variability in thought content was indexed by the factor score in the Think Aloud task and the ratings of the freely moving thought question in the Ecological Momentary Assessment component. These planned simple main effects analyses indicate higher levels of hyperactive symptoms correspond with increased variability in thought content in the conditions with lower levels of deliberate constraints in both the (**a**) Think-Aloud (i.e., the unconstrained condition in red) and the (**b**) Ecological Momentary Assessments (i.e. task-unrelated thoughts in red).

Fixed effects	b	$CI_{95\ low}$	$CI_{95\ high}$	se	df	t	*p*
Hyperactivity							
Intercept	2.52	1.45	3.59	0.55	1395	4.60	< 0.001
Task-relatedness	− 0.41	-1.76	0.94	0.69	1395	− 0.59	0.553
Hyperactive symptoms	0.03	0.01	0.05	0.01	89	3.12	0.002
Task-relatedness x hyperactive symptoms interaction	− 0.02	− 0.05	0.00	0.01	1395	-2.03	0.042
Inattention							
Intercept	3.43	2.50	4.37	0.48	1395	7.16	< 0.001
Task-relatedness	-1.68	-2.85	− 0.52	0.59	1395	-2.83	0.005
Inattentive symptoms	0.01	0.00	0.03	0.01	89	1.64	0.105
Task-relatedness x inattentive symptoms interaction	0.00	− 0.02	0.02	0.01	1395	− 0.19	0.847

Table 2. Interaction models predicting variability in thought content captured with ecological momentary assessment by task-relatedness and ADHD symptoms. Separate models tested the interaction between ADHD symptoms (hyperactive, top or inattentive, bottom) and task-relatedness (unintentional task-unrelated vs. task-related indexing lower vs. higher levels of deliberate constraints respectively). The reference level for task-unrelatedness was task-related thought. Results of the planned simple slope main effects analysis to the significant interaction between hyperactive symptoms and task-relatedness are shown in Fig. 2b.

there was a significant interaction ($p = .042$). Planned simple main effects analysis showed that the experience of freely moving thoughts became more pronounced with increasing levels of hyperactive symptoms for task-unrelated thoughts ($b = .03$, $t(90) = 3.09$, $p = .003$) but not for task-related thoughts ($b = .01$, $t(90) = .59$, $p = .554$). This indicates that levels of hyperactive symptoms were positively associated with thought content variability during lower levels of deliberate constraints.

The model involving inattentive symptoms revealed a significant main effect of task-relatedness ($p = .005$), such that task-unrelated thoughts were associated with higher levels of freely moving thoughts than task-related thoughts. Neither the main effect of inattentive symptoms ($p = .105$) nor the interaction were significant ($p = .847$). Planned simple main effects analysis confirmed that inattentive symptoms were not predictive of freely moving thoughts for either task-related ($b = .01$, $t(90) = 1.65$, $p = .102$) or task-unrelated thoughts ($b = .01$, $t(90) = 1.62$, $p = .109$). Details about the random effects and the simple main effects analysis for both models are reported in Supplementary Tables S3-S4.

Discussion

The present study provides converging evidence demonstrating that individuals reporting higher levels of hyperactive, but not inattentive, symptoms of ADHD experience higher levels of thought dynamics both in a naturalistic setting and in daily life. Importantly, this pattern was more pronounced in situations with lower levels of deliberate constraints. The Think Aloud task revealed that participants with high levels of hyperactive symptoms displayed heightened variability in thought content (i.e., shorter, semantically dissimilar thoughts transitioning abruptly and covering more topics) during conditions of minimal deliberate constraints. Similarly, the ecological momentary assessment component of the study revealed that participants with higher hyperactive symptoms also showed increased thought content variability (i.e., experiencing their thoughts as more freely moving) when deliberate constraints were lower during unintentional task-unrelated thoughts. Overall, these results suggest that hyperactive ADHD symptoms are linked to increased thought dynamics when there are lower constraints on thought content. These results are consistent with hypotheses put forth by the Dynamic Framework of Spontaneous Thought[4] and highlight the potential clinical value of naturalistic assessments of thought dynamics in ADHD.

Hyperactive, but not inattentive, ADHD symptoms are associated with increased thought content variability

Across two experiments in a naturalistic setting and in daily life, we found that individuals with higher levels of hyperactive, but not inattentive, ADHD symptoms showed increased variability in thought content. Prior work has shown that both hyperactive and inattentive ADHD symptoms were associated with a higher propensity to experience task-unrelated thoughts[10,14–18], a pattern confirmed by the present dataset. Yet, heightened thought content variability was only observed in individuals with higher levels of hyperactive symptoms, with both experimenter-assessed (i.e., larger thought variability factor scores in the unconstrained Think Aloud condition) and self-assessed (i.e., more freely moving thoughts when they were task-unrelated in the daily surveys) measures. These results are consistent with the observation that the physical restlessness experienced by individuals with high levels of hyperactive symptoms becomes internalized in adulthood[9–11], with the impact of such internalization shown to manifest in racing thoughts[11]. These results shed some light onto the cognitive profile of individuals with hyperactive ADHD symptoms.

The positive relationship between dynamics of thought and hyperactive symptoms in the constrained condition of the Think Aloud was not significant. A similar null result was observed for the more constrained level (i.e., task-related thought) of the ecological momentary assessment component of the study. One possible explanation is that the mean level of ADHD symptoms in this sample is one standard deviation higher than the

mean level of ADHD symptoms in the general population; therefore, it could be the case that future studies may detect significant differences in variability in thought content even in the constrained condition when examining this pattern in a group with a broader range of hyperactive ADHD symptoms that extend into the lower end.

We found that inattentive symptoms were not associated with thought variability in either study component. They were also not linked to associative transitions in the Think Aloud tasks. Past work has reported increased tendencies to experience task-unrelated thoughts that are constantly on the go and fleeting from one to another as well as multiple thoughts at the same time, via questionnaires, in individuals with inattentive ADHD symptoms[22]. Although we also observed a positive relationship between inattentive symptoms and task-unrelated thoughts, we did not detect any association with thought dynamics. One potential explanation is that altered patterns of thought dynamics in individuals with inattentive symptoms may manifest in a way that is not captured by our measures of thought dynamics. Alternatively, it is also conceivable that inattentive symptoms may only manifest in differences in thought content or may be limited to the previously observed general propensity to experience task-unrelated thoughts[10,14–18].

Neither the hyperactive nor inattentive ADHD symptoms correlated with the total number of words generated capturing speech production. Past work examining the relationship between ADHD and speech production has shown mixed results. Whereas some studies observed a positive association[37,38,40], others reported null associations[13,39,41]. Although we also found no evidence of such relationship, it is possible that comparing our sample to a control group with low levels of ADHD symptoms may yield different results. Further work is necessary to elucidate how speech production maps onto the subjective experience of racing thoughts assessed via questionnaires in ADHD and to what extent this putative relationship depends on the heterogeneity of symptoms.

Our findings about heightened variability in thought content are also relevant to understanding studies revealing that individuals with high levels of ADHD symptoms are more likely than those with low levels to display explorative behavior as part of their cognitive profile, which often manifests as frequent and pronounced behavioral switches. This has been observed across cognitive domains, including decision making[42], foraging[43] and visual-spatial searching[40]. These exploratory tendencies have also been reported in verbal fluency tasks, requiring one to generate sequences of words one-at-a-time under a constrained condition (e.g., words that start with 'P' or that belong to the category 'animals') or with no constraints. In these studies, individuals with higher levels of ADHD symptoms tend to make more frequent semantic shifts in the absence of constraints[39,40], resulting in the production of more, but smaller, clusters of semantically related words[41]. These experimental manipulations parallel the differing levels of deliberate constraints in our tasks and highlight that a similar approach focusing on single words may also capture changes in thought content. Among these past studies, only Addicot and colleagues[42] distinguished between hyperactive and inattentive symptoms, reporting that only the former were associated with more exploratory behaviors during decision making. Our results complement these previous findings, highlighting that the symptoms of ADHD may be manifested in different cognitive domains, including variability in thought content as well as exploration. Importantly, our results make a unique contribution by showing that hyperactive and inattentive ADHD symptoms are differentially linked to thought dynamics using paradigms that approximate our everyday behavior (i.e., thinking aloud) and that capture the nature of our thoughts in daily life (i.e., ecological momentary assessment). An important direction of future research may examine cognitive mechanisms underlying these conceptually similar cognitive correlates of different types of ADHD symptoms.

Our results corroborate existing evidence demonstrating the heterogeneity of ADHD symptoms and underscore the value of considering different facets of ADHD when examining thought dynamics. While it is common for individuals with ADHD to endorse multiple clusters of symptoms, the clinical and real-world impacts of these different symptom types may still vary widely. Future studies may benefit from examining whether specific aspects of thoughts are selectively linked to a particular type of symptom, which will extend our understanding of the diverse cognitive processes that reflect the manifestation of the heterogeneity in ADHD.

ADHD is associated with higher levels of behavioral and neural fluctuations during both external and internal attention

Our overall results are consistent with prior research on ADHD. Past studies have reported high levels of behavioral fluctuations during external tasks (e.g., decision making, exploratory behavior, and visuo-spatial search) in individuals with ADHD[40,42,43]. Our findings of increased thought variability in this population complement and extend existing research by suggesting that these fluctuations are not only observed in external domains but also in one's internal world. This is especially the case in the absence of a task, as with the unconstrained condition of the Think Aloud task. A core feature of ADHD concerns difficulty paying attention to external tasks (i.e., the 'A' in ADHD), and our results additionally indicate that hyperactivity features of ADHD are also associated with difficulties focusing inner thoughts on a particular topic. Notably, these behavioral and thought fluctuations in both external and internal contexts are in line with neuroimaging research, which have shown ADHD is associated with increased variability in the brain signal during task engagement[44], resting state[45,46], as well as freely moving and task-unrelated thoughts[21]. These various lines of behavioral and neural evidence, along with our study, converge on the notion of high levels of variability in both externally and internally-oriented processes in ADHD, which is manifested in behavior, thought, as well as brain signals.

The importance of context: Thought dynamics emerging in situations of lower deliberate constraints may be particularly clinically relevant

The observed differences in thought dynamics during times of lower deliberate constraints highlight the importance of the context in which people experience thoughts, and suggest that situations of minimal deliberate constraints may be optimal for capturing thought dynamics. Such an approach was successfully used to highlight

the cognitive signature of the brooding mind[3]. Future research should further investigate the role of context in determining the cognitive markers of different personality features and clinical disorders.

These results showing context-dependent effects on thought dynamics in our sample may also illuminate a pervasive phenomenon in the assessment of cognitive performance in ADHD, referring to a notable misalignment between self-reported and objectively measured abilities[47,48]. There is robust empirical evidence[47–49] that individuals with ADHD report significant executive dysfunction and attentional problems in their day-to-day life (when deliberate constraints are presumably relatively lower) but often perform normally on formal tests of attention and executive function in lab-based settings (where deliberate constraints are presumably relatively higher). Thus, our results suggest that it is possible that the difficulties encountered in everyday life by individuals with ADHD may reflect an inability to focus their thoughts (due to their heightened thought dynamics) resulting from being in everyday environments that are characterized by low levels of deliberate constraints. In contrast, their ability to constrain the content of their thoughts may be facilitated in a more structured clinic or laboratory setting. Results of the present work suggest that hyperactive symptoms may be associated with greater discrepancies in cognitive performance between naturalistic and lab-based settings. Future work addressing this question empirically may be useful to inform the interpretation of cognitive assessments in individuals with different symptom types.

Think aloud: A method to capture unconstrained thoughts

Our study, along with others, highlights the value of the Think Aloud paradigm as a useful methodological approach to the study of thoughts. Whereas ecological momentary assessment facilitates the study of self-reported thoughts in terms of content and dynamics in daily life across time and varying contexts, the Think Aloud method provides a wealth of data about these measures without relying on self-assessment and in contexts that can be manipulated. This method has now been successfully applied to predict different outcomes beyond ADHD, including brooding[3], creativity[26], and age-related affective outcomes[50], highlighting its predictive validity. Across two different samples from different countries in the present study (Canada) and past studies (U.S.A.), we have found that capturing resting-state thoughts with the Think Aloud task yields similar experiences (e.g., levels of censorship and similarity to daily thoughts) and measures of dynamics (e.g., mean number of words per thought), cementing its reliability (see Supplementary Table S7). In summary, the Think Aloud is a short, easy to implement, and ecologically valid method that can provide access to thoughts that are difficult to capture (i.e., unconstrained thoughts) and can contribute greatly to identifying the cognitive markers associated with clinical conditions.

A notable methodological difference between the version of the Think Aloud used in the current study and prior use of the procedure was that participants in this sample performed the task in their homes, which is a highly familiar and presumably perceptually richer environment compared to a minimally stimulating environment in the laboratory[3,26]. The fact that we observed meaningful individual differences despite this important difference in setting reinforce the reliability of the task. Additionally, participants in both the present study and in previous study[50] completed the Think Aloud task over Zoom in the setting of their choice, suggesting the task can be implemented across highly controlled laboratory settings as well as naturalistic environments. It is a promising methodology for recruiting from more diverse groups in the community.

Limitations & future directions

Our results should be interpreted with the following considerations. While our results demonstrate a tendency for individuals with high hyperactive symptoms to have more variable unconstrained thoughts, they do not inform as to whether it is a desirable or undesirable outcome. Indeed, freely moving thought have been associated with more positive affect[19,51] whereas task-unrelated thoughts have been linked to more negative affect[52,53]. An important direction for future research involves exploring the affective consequences associated with increased thought variability in this population. Although our current study did not obtain measures of affective valence, we performed an exploratory thought valence analysis which can be found in the Supplementary Materials (also see Supplementary Table S5).

Next, the options for topics (i.e., family or friends) in the constrained Think Aloud condition was one of many topics that we could have selected, and we expect that the topic may influence the sensitivity of the task in detecting relevant individual differences in thought dynamics. Developing a methodology to systematically manipulate the levels of deliberate constraints in both Think Aloud and ecological momentary assessment would be a useful endeavor in order to further explore how the relationship between thoughts and various outcomes relevant to mental health and other personality features may be modulated by context.

Moreover, the use of task-relatedness as a proxy for deliberate constraints in the ecological momentary assessment component is arguably a theoretical assumption. While the results were consistent with our hypothesis, further work should consider more direct ways to assess levels of deliberate constraints in everyday life.

Finally, the present sample included a disproportionate number of females, which raises a few points for consideration. This may represent a limitation in the generalizability of our findings, though the patterns of our results remained the same after accounting for gender. Additionally, the gender ratio in our study may not be representative of the ADHD population, considering males are more likely to be diagnosed than females[54]. Given that females are often under diagnosed, our study may provide insight into a potential diagnostic tool that is sensitive to hyperactivity features in females. Future investigations could attempt to replicate our findings in a sample with more equal representation of gender groups to increase the generalizability of these findings.

Our findings of increased thought variability associated with hyperactivity features of ADHD have potential implications for clinical practice. For example, our results may inform interventions for those with hyperactivity features. Specifically, given that individuals with hyperactivity ADHD features displayed more focused levels

of thought during the constrained condition of the Think Aloud task, this suggests that these individuals may potentially be more responsive to structured therapy settings, which can reduce the likelihood of their thoughts to move freely from topic to topic. Future studies may investigate the therapy settings that are optimal for individuals with different features of ADHD.

Concluding remarks

In conclusion, the current study established a robust positive association between hyperactive ADHD symptoms and thought dynamics, with converging evidence from two studies using different methodological approaches. These findings highlight the importance of considering the context in which thoughts arise when assessing thoughts in ADHD. Our work also underscores the value of combining the Think Aloud task with ecological momentary assessment as complementary approaches for capturing ongoing thoughts, with important implications for a wide range of clinical conditions.

Method

Participants

Participants were recruited from the community as well as from a registry of individuals with self-reported ADHD, and were screened according to four eligibility criteria: (1) had access to an email account, a cell phone, and a personal computer with a webcam and microphone, (2) were fluent in English, (3) had normal or corrected-to-normal eyesight, and (4) were between 18 and 80 years of age. Enrollment from the ADHD registry ensured representation of cases with severe symptoms, but an ADHD diagnosis was not required to participate. One participant was removed from the final analysis due to failure to follow the instructions during the Think Aloud tasks. The final sample consisted of 91 participants (72 Females, 19 Males; age: $M = 39.0$, $SD = 14.5$, range = 19–79; ethnicity: 63 white/European Canadian, 8 multiethnic, 6 East Asian, 6 South Asian, 3 Southeast Asian, 1 black/Caribbean/African Canadian, 1 Hispanic, 2 other, 1 preferred not to say). All participants provided informed consent and were compensated with $40 CAD in the form of an electronic gift card for taking part in the study. All procedures were performed in accordance with the relevant guidelines and regulations and approved by the University of Calgary's Conjoint Faculties Research Ethics Board (REB21-1513).

Summary of procedures

Given the study was conducted during the COVID-19 pandemic, data collection took place online via Zoom (Zoom Inc). During the online session, participants first completed a demographic questionnaire. They then performed one unconstrained and one constrained version of the Think Aloud task, each lasting 10 min each. Participants were then asked to complete six daily surveys over seven consecutive days as part of the ecological momentary assessment component of the study, which started two days later. Participants were also asked to complete a questionnaire assessing varying features of ADHD symptoms.

Capturing thought dynamics using think aloud tasks

Think aloud paradigm

To assess thought dynamics in a naturalistic environment, participants completed two versions of the Think Aloud task, each lasting 10 min, over a single Zoom session. During the session, they were first given the opportunity to practice 'thinking aloud' for three minutes, to ensure they became familiar with the process and to clarify questions with the experimenter that arose during this practice. Following the practice, they first performed an unconstrained Think Aloud task in which they were not provided with any prompt as to what to think about. During this task, they continuously voiced aloud in real-time the content of their mind, whether it be perceptual, imaginative, or somatosensory, following the procedure of Raffaelli et al.[3,26]. Participants then performed a constrained Think Aloud task. This was identical to the unconstrained version, with the exception that participants were prompted to think about a single topic: family or friends. Instructions to participants are reported in the Supplementary Materials. The unconstrained and constrained versions of these two Think Aloud tasks served as proxies for lower and higher levels of deliberate constraints, respectively.

To minimize the effect of social presence, the experimenter instructed the participant to find a quiet place where they would be undisturbed during the task. Additionally, the experimenter clearly stated to the participants that they would leave the room in which the computer was located during the entirety of each task, after turning their camera off to reduce distraction. To minimize the effect of self-consciousness, participants were asked to either use the 'hide yourself' function or minimize their Zoom window so that they did not see themselves as they performed the task.

After each Think Aloud session, participants answered several questions about their experience of the task, including the extent to which (1) their Think Aloud thoughts represented their daily thought ("To what extent were your verbalized thoughts similar to your everyday thoughts?") and (2) they censored themselves ("How much did you censor yourself during the task?"). These questions were answered on a scale from '0 = Not at all' to '100 = Extremely'.

Quantification of thought dynamics

Participants' Think Aloud data were recorded and later transcribed. Two trained raters quantified the number of thoughts by identifying and categorizing the transitions between topics as either strong or associative, following the method outlined by Raffaelli et al.[3,26]. This quantification of strong and associative transitions derived from raters reflect two related measures of thought dynamics. Transitions are considered strong whenever the shift between topics is abrupt such that nothing seems to link the current topic to its predecessor. Transitions are considered associative when a topic and its predecessor are related in some capacity such that the current thought was elicited by the content of the preceding thought, exemplified by the phrase "It reminds me of…".

One can think of these shifts in content in terms of Venn diagrams. Strong transitions are illustrated by two non-overlapping circles ("Yesterday's sushi was amazing." / "I can't wait to start reading this new book on consciousness.") and associative transitions are represented by two partially overlapping circles indicating some commonality in content ("It's annoying to have to wait another year for the next Mission Impossible movie." / "Speaking of waiting, the wedding is two months away"). Note that although participants were restricted to think about family or friends in the constrained version of the Think Aloud, we rated transitions as strong or associative based on whether jumping from one person to another felt abrupt (strong transition: "My dad just mentioned it has been raining for 3 months". / "My sister mentioned I should watch Archer.") or seamless (associative transition: "I need to find a birthday present for my niece." / "Shoot, I forgot to wish my friend X a happy birthday.").

Each rater provided the following measures for each Think Aloud session: the number of words per thought, the number of themes, and the number of strong transitions and associative transitions. The inter-rater reliability was excellent for all measures (*Spearman-Brown*'s > 0.90) for both Think Aloud tasks, except for associative transitions in the unconstrained Think Aloud for which it was good (*Spearman-Brown* = 0.83). Spearman correlations between raters for each measure for both the unconstrained and constrained Think Aloud and their corresponding scatterplots can be found in Supplementary Figure S1 and additional details about inter-rater reliability can be found in Supplementary Table S6. We also extracted the total number of words generated during each Think Aloud condition. For all subsequent analyses, we used the mean across both raters' scores for all metrics of thought dynamics.

We also assessed the semantic similarity in the thoughts participants generated in each of the Think Aloud task. Semantic metrics were assessed using the natural language processing library SpaCy in Python (https://spacy.io/), one of the fastest and most accurate natural language processing tools available[33,34] via the richest vector model (514k unique vectors) pipeline en_core_web_lg (v. 3.7.1). For each rater's transcripts of each Think Aloud session of each participant, we calculated the overall semantic similarity metric. It estimates the similarity in thought content between all possible pairwise permutations of thoughts (i.e., similarity $t_1 - t_2$, similarity $t_1 - t_3$, … similarity $t_{\text{final thought}-1} - t_{\text{final thought}}$), and then computes the mean of all these semantic similarity scores (ranging from 0 to 1 where 0 is extremely dissimilar and 1 extremely similar). Each participant thus receives four overall semantic similarity scores: one from each of the two raters for each of the two Think Aloud sessions. The inter-rater reliability for the overall semantic similarity metric for both Think Aloud sessions was good (*Spearman-Brown's* > 0.80 for both sessions, see Supplementary Table S6). Finally, we computed the mean semantic similarity score for each Think Aloud session of each participant averaged across the two raters.

In the unconstrained Think Aloud condition, participants generated on average 1224 words (*SD* = 393, range = 323–2220). Participants had an average of 29 thoughts (SD = 13, range = 8–65) of an average length of 53 words (*SD* = 35, range = 12–193), separated by an average of 19 strong transitions (*SD* = 12, range = 0-74.5) and 11 associative transitions (*SD* = 9, range = 0-58.5). The average overall semantic similarity between all thoughts was .73 (*SD* = .09, range = .42-.87). Of note, these central tendencies are strikingly similar to those reported previously by Raffaelli et al.[3], a finding that further supports the reliability of the task and scoring protocol. We compared the descriptive measures between our study and Raffaelli et al.'s 2020 study in Supplementary Table S7.

In the single-topic constrained Think Aloud, participants generated an average of 1307 words (*SD* = 333, range = 408–2346). Participants had an average of 26 thoughts (*SD* = 19, range = 5–58) of an average length of 66 words (*SD* = 41, range = 14–209), separated by an average of 9 strong transitions (*SD* = 7, range = 0–37) and 15 associative transitions (*SD* = 9, range = 0–39). The average overall semantic similarity between all thoughts was .76 (*SD* = .07, range = .43-.87).

Capturing thought dynamics using ecological momentary assessments

To assess thought dynamics in everyday life, participants completed a weeklong ecological momentary assessment. During the online session, following the Think Aloud tasks, participants received detailed instructions and training by the experimenter to ensure their understanding of the ecological momentary assessment procedure and questions asked at each survey.

Participants were sent six probes a day for seven consecutive days. The probes were sent at pseudo-random times during a 10-hour time window based on participants' self-reported typical waking hours. Each probe contained a link to an identical Qualtrics survey asking questions about participants' most recent thought. To assess thought dynamics, the main question of interest was "Were your thoughts freely moving from topic to topic?", with response options on a Likert-type scale ranging from '1 = Not freely moving at all' to '7 = Extremely freely moving'. Responses to this question reflect a self-report measure of variability in thought content. In another relevant question assessing task relatedness, participants were asked to select one response to the question "Were your thoughts on-task, mind wandering without intention, or mind wandering with intention?", whereby mind wandering was defined as thoughts unrelated to the ongoing task. Although the task design distinguished between task-unrelated thoughts with and without intention for the purpose of addressing other research questions, it also serves an important purpose for the present study. Specifically, we focused our analyses on unintentional task-unrelated thoughts; given that thoughts occurring without one's control are, by definition, unlikely to be characterized by high levels of deliberate constraints, we excluded the intentional mind wandering thoughts from our analyses (as this would represent an overlap in our construct of interest). For comprehensiveness, we report the results of the EMA analysis described below in which both task-unrelated subtypes were collapsed into a single variable reflecting the task-unrelatedness of thoughts in Supplementary Tables S8-S9 (also see Supplementary Figure S2). Participants answered three other questions that were aimed to address other research questions beyond the scope of this study (in manuscripts that are under review). These questions are reported in the Supplementary Material for transparency.

Participants were instructed to respond to the survey as soon as they received it, and to skip it if they noticed more than 30 min had passed since it was sent. Considering the small number of questions, surveys that took more than 5 min to be completed were excluded from analyses as this would likely reflect multitasking or disruptions that could compromise memory accuracy. We removed 501 surveys based on these criteria. In total, 1880 probes (49%) went into the final analysis, with participants completing an average of 20.66 probes ($SD = 5.23$, range = 8–28) that fulfilled the above criteria.

Across all probes, participants reported their thoughts to be moderately freely moving ($M = 3.47$, $SD = 1.7$, range = 1–7). The average level of freely moving thoughts was 4.25 ($SD = 1.53$) for task-unrelated thought and 2.33 ($SD = 1.27$) for task-related thoughts. Of the 1488 probes used for the analysis, 753 were classified as task-unrelated and 735 as task-related. On average, participants reported having task-unrelated thoughts 49.31% of the time and task-related 50.69% of the time ($SD = 21.96$, range = 0-100). Of the task-unrelated thoughts, 65.76% were unintentional, which were the only responses included in subsequent analyses. The tendency to have task-unrelated thoughts in daily life was related to both hyperactive ($r(89) = .34$, $p = .001$) and inattentive ($r(89) = .34$, $p = .001$) symptoms, consistent with prior work establishing a relationship between proneness to have task-unrelated thoughts and both types of ADHD symptoms[14,17].

Questionnaires

Participants completed the short version of the Conners Adults ADHD Rating Scale (CAARS[35]), a 26-item questionnaire with subscales assessing the presence and severity of several features of ADHD: hyperactivity, inattention, impulsivity, and problems with self-concept, as well as a general ADHD index (Cronbach alpha range = .49 – .91[36]). Standardized T-scores accounting for participants' age and gender were calculated along the hyperactivity and inattention subscales of the CAARS as specified in the assessment protocol. For the purpose of this study, we focused only on the hyperactivity and inattention subscales, because they represent the core features of the disorder and are most theoretically linked to thought dynamics.

The average hyperactive symptoms T-score was 59.96 ($SD = 10.23$, range = 34–82) and the average inattentive symptoms T-score was 64.10 ($SD = 13.48$, range = 36–90). As the normative T-score in the general population for both hyperactive and inattentive symptoms is 50, this places our sample on average approximately one standard deviation above the mean on both types of symptoms.

Statistical analysis

All statistical analyses were implemented in R (version 4.4.0) using R Studio (version 2024.04.1 + 748). Age and gender were included as covariates in all initial statistical models but given that their inclusion did not alter the patterns of results, analyses reported below did not include these covariates in the model for the sake of brevity. We report the results with age and gender as covariates in Supplementary Tables S10-S12.

Think aloud

All Think Aloud derived variables were Box-Cox transformed to normal distributions and then scaled (by subtracting the mean and dividing by the standard deviation). Due to the theoretical and actual strong relationships between the number of strong transitions, number of themes, mean number of words per thought, and overall semantic similarity on both Think Aloud sessions (range of r's = |.38| - |.82|), we created a single composite score for each Think Aloud session using eigenvalue decomposition. For both sessions, such a factor explained above 71% of the variance. The factor scores reflect a combination of high levels of strong transitions and number of themes, a lower mean number of words per thought, and more semantically distant thoughts. Details about the strength of the relationships between variables and their eigenvectors are shown in Supplementary Figure S3. We will henceforth refer to this construct as the variability in thought content factor score to represent strong transitions and their related metrics, which will be used for subsequent statistical analysis. We report the relationship between each of the variables composing this factor and the outcome variables in Supplementary Tables S13-S16.

In addition to this factor score representing thought content variability, we also examined two other commonly reported measures of this task[3,26]: associative transitions and total number of words generated. Associative transitions refer to transitions in which the content of one thought leads to another, reflecting a semantic association between consecutive thoughts. Given that thoughts are conceptualized to jump abruptly between seemingly unrelated topics in ADHD[13], we did not expect any relationship between this variable and ADHD symptoms (i.e., fewer semantically associated transitions as ADHD symptoms increase). We also examined the total number of words generated, as a proxy for higher speech production. As past findings linking higher speech production and ADHD have been mixed[13,37–41], we had no specific predictions about this metric.

We conducted separate linear regression models for each type of ADHD symptoms, predicting each of the three thought dynamics variables (i.e., variability in thought content factor score, number of associative transitions, total number of words generated) from ADHD symptom (hyperactive or inattentive T-scores in their corresponding model), with an interaction between condition (unconstrained vs. constrained Think Aloud) and ADHD symptoms. Given the experimental manipulation of levels of deliberate constraints across conditions and our predictions about thought content variability as a function of deliberate constraints, we implemented a priori simple main effects analysis to follow up on each interaction, which involved assessing the main effect of ADHD symptoms on thought content variability for each Think Aloud condition.

Ecological momentary assessments

To determine whether variability in thought content as characterized by freely moving thought was influenced by ADHD symptoms in everyday life, we implemented two separate multi-level model analyses for hyperactive and inattentive symptoms. Each model included participants as the nested structure and freely moving thoughts

as the dependent variable. The predictors included in this model were task-relatedness as a first level fixed effect, as a proxy for the level of deliberate constraint (with task-related thoughts reflecting a higher level of deliberate constraint than unintentional task-unrelated thoughts), and ADHD symptoms (hyperactive or inattentive) as a second level fixed effect. Considering we expected thought dynamics to be more pronounced in situations where deliberate constraints are lower, the models also included an interaction between task-relatedness and ADHD symptoms. The multi-level models were implemented with the nlme package using the Maximum Likelihood method.

To identify the optimal model, we compared models of increasing complexity using a stepwise approach, from a simple regression model with a single intercept and a single slope to a model with random intercepts, random slopes, and an interaction between first and second level effects. The details of these model comparisons are reported in Supplementary Table S17. The unconditional mean model suggested that participant-level information explained about 20% of the variance ($ICC = 19.75\%$) and this model performed better than the simplest model with a single intercept for the entire sample ($\chi^2 = 250.32$, $p < .001$), confirming the necessity to include participants as a random intercept. Models of increasing complexity performed significantly better than their predecessors. The best model prior to the introduction of second level predictor included both random intercepts and slopes for the first level predictor.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

B.L.C., J.A.H., and J.W.Y.K. designed the research. S.R., A.G., A.K. and J.B. collected and curated the data. Q.R. analyzed the data. Q.R. and J.K. wrote the paper. All authors provided substantial intellectual contributions to the final draft of the paper.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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