Investigating Barriers and Facilitators to Wearable Adherence in Fine-Grained Eating Detection

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***Abstract*—Energy balance is one component of weight management, but passive objective measures of caloric intake are non-existent. Given the recent success of actigraphy as a passive objective measure of the physical activity construct that relieves participants of the burden of biased self-report, computer scientists and engineers are aiming to find a passive objective measure of caloric intake. Passive sensing food intake systems have failed to go beyond the lab and into behavioral research in part due to low adherence to wearing passive monitoring systems. While system accuracy and battery lifetime are sine qua non to a successfully deployed technology, they come second to adherence, since a system does nothing if it remains unused. This paper focuses on adherence as affected by: 1) perceived data privacy; 2) stigma of wearing devices; 3) comfort. These factors highlight new challenges surrounding participant informed consent and Institutional Review Board (IRB) risk assessment. The wearables examined include neck- and wrist-worn sensors, and video camera-based systems. Findings support the potential for adherence using wrist- and shoulder-based video cameras, and personalized style-conscious neck-worn sensors. The feasibility of detecting fine-grained eating gestures to validate the machine learning models is shown, improving the potential of translation of this technology.**

***Index Terms*—Eating Detection; Privacy; Stigma; Camera; Wearables; Sensors; Obesity; Annotation; Ground Truth; Adherence.**

I. Introduction

Studying eating behaviors of obese and non-obese participants is essential to understanding problematic eating behaviors to bridge the gap to intervention design. Food frequency questionnaires, food diaries, and 24-hour dietary recalls are the main measures of food intake. These self-report methods are predisposed to bias in recall and response, imposing a high burden on participants, especially longitudinally. Passive sensing wearable technology has the potential to detect how (number of feeding gestures, swallows and eating duration), where (at home, a restaurant), when (time of day), and with whom (alone, or with friends or family) people eat. These systems could reduce participant burden, and gather data in natural contexts. Numerous studies have designed wearables [1], [2], [3] or have used commercial wearables [4], [5] to detect eating behaviors. However, to detect behaviors, participants must adhere to wearing the sensors. Studies continuously show challenges in willingness to adhere, but little is known as to why.

Cameras have been used to provide objective course detection of eating moments [6], [7]. Nebeker et al. [8] report one-third of participants feeling uncomfortable wearing a camera, highlighting the importance of protecting participant privacy. However, only one system and location were studied.

King et al. [9] investigated the stigma of a wearable camera (SenseCam) and a wrist-worn sensor (LARK) using Tobii eye-tracking glasses to count the number of fixations participants had on the devices. While results of tracking eyes show promise of low intrusion and stigma in-lab, perceived stigma may be sensed differently in real-world contexts.

Knight et al. [10] discuss the importance of user comfort in assessing wearables, stressing the analysis of not only physical factors such as size, weight distribution, location of device, but also anxiety and emotion.

The purpose of this study, ADHERE-EAT, is to examine the challenges of using eating related wearables including participant privacy, stigma, and user-comfort, which impact adherence to wearables, culminating in an optimal passive wearable sensor suite for fine-grained eating detection that participants are likely to wear in the field.

II. Related work

Ground truth labels of activity are essential in gesture recognition research to validate the predictive power of machine learning algorithms. To date, however, ground truth labels have predominantly been developed using controlled lab settings, which do not capture the complexity found in natural settings, resulting in poor generalizability. To improve understanding of eating habits such as number and rate of swallows, chews, and feeding gestures, research translation out of the lab is critical.

Dong et al. [11] use a smartphone app for free-living participants to log the start and end of their eating moments to establish ground truth for a day. Ten participants (23%) were excluded due to low reporting compliance and missing meals. To avoid these problems, researchers have used wearable cameras [4].

Thomaz et al. [4] asked participants to don a camera on a lanyard to capture a still image every 60 seconds to aid in end-of-day eating recall. This minimized participant burden throughout the day, but the images do not capture fine-grained activities that occur at a second or subsecond scale. An average duration for a feeding gesture is 2.8 seconds (from time of food pick up to bite, and hand back-to-rest) [12].

Hoyle et al. [13] studied how sharing images in social networks among life-loggers using a mobile phone to capture an image every 5 minutes impacts concerns of privacy. Raij et al. [14] showed that people were concerned with divulging their physiological state (stress) and method of commuting to and from work, but less concerned with sharing data with researchers compared to the public. The researchers examined privacy issues with psychological and behavioral data captured by wearables.

It is known that wearable adoption is impacted by socio-cultural norms that effect a person's desire to fit in, such as stigma and fine tuning to a user's specific needs [15]. The current study, ADHERE-EAT, addresses user specific needs by enabling them to select the sensor of their choice, enabling personalization in hopes of reducing perceived stigma.

Comfort analysis also aids in understanding participant burden and acceptability of sensors. Fontana et al. [16] showed using a Comfort Rating Scale that participants were more comfortable using a chewing sensor close to the ear compared to a swallowing sensor which used a neck-worn throat microphone. The ADHERE-EAT study aims to build upon this related work by addressing adherence (privacy, user comfort, and social acceptability) of using a wearable device to collect fine-grain eating behaviors outside of a controlled laboratory setting in people with obese, overweight and normal BMI.

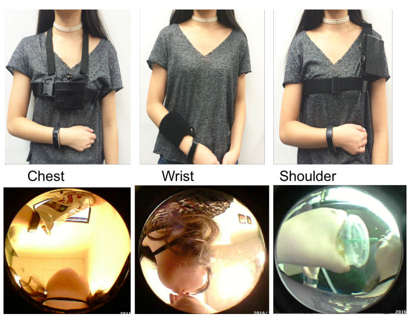

Fig. 1. Three camera locations used in the study.

III. Methodology

A. ADHERE-EAT System

1) Video Camera Design: Three prototypes of a wearable video camera (with audio) were designed (with an augmented fish-eye lens) to continuously record participant behavior to capture fine-grained eating activity. Placement of a video camera in different positions around the upper torso of the body and wrist provided different fields of view, varying the ability of the system to capture different eating-based features. Figure 1 depicts the three designs worn by a participant along with their corresponding fields of view.

The video camera model used was the Qcam QSD-722 designed as a hidden video camera recorder, capable of recording 24 hours of video with IR night vision.

The shoulder camera lens faces the participant's dominant hand rather than pointing outward, to minimize bystander discomfort, [8] although bystanders to the side of the participant are noticeable. The chest-worn camera lens is directed at a 45-degree angle from North (up), although this was later adjusted for obese participants. In this design, the lens would capture bystanders directly in front of the participant. The wrist-worn camera lens is positioned on the inner side of the dominant hand's wrist at a 45-degree angle away from the wrist.

Fig. 2. Choices of neck-worn devices (1:Phiten, 2:Lace, 3:Velvet, 4:3D Printed, 5:Fabric, 6:Throat Microphone)

2) Neck-Worn Sensor Design: Figure 2 illustrates the six neck-worn sensor prototypes that were provided as options for the participants. Cohen et al. [17] shows that 62% of people would wear a neck-worn sensor depending on the style. Some styles were commercial (like the throat microphone), other styles were designed in the lab, equipped with a piezoelectric vibration sensor and a microcontroller board capable of sampling and transmitting sensor data to a mobile phone via Bluetooth.

3) Wrist-Worn Sensor Design: The historical nature of wearing a wristwatch lends itself to the implementation of a wrist-worn device. Given Microsoft Band 2 (mBand2) [18] open API platform enabling researchers to access raw sensor data, this paper focuses on using the mBand2 to test the potential for adherence to a wrist-worn sensor. The wrist-worn device is worn on the dominant hand in order to increase the likelihood of detecting an eating gesture.

B. DAT: Deletion and Annotation Tool

Empowering the user to delete and label the video with start and end times of eating episodes enables validation of our machine learning algorithms. The current video camera system records data on 64 GB SD Cards inserted inside the camera, generating on average a new file every 20 minutes. Continuously recording 12 hours of video generates at least 36 files. To allow the participants to view and delete the videos, a web-based deletion and annotation interface named DAT was designed. The participants can label different segments of the video to annotate the start and end of each eating episode, and they can also set the start and end of a segment to delete.

C. Experiment

This study was approved by Northwestern University IRB (Protocol #STU00203801). Figure 3 depicts the different stages of the experiment, and Table II shows the different measures used at the varying stages. The first is pre-study to screen for eligibility (age > 18, normal/overweight 19-30 BMI, obese > 30 BMI), collect participant problematic eating habits (emotional, impulsive, hedonic and binge eating), and privacy attitudes which may impact their use of wearables.

In the structured setting, participants were assigned a random video camera design (either chest, wrist, or shoulder), the

Fig. 3. Stages of ADHERE-EAT Experiment

mBand2 wrist-worn sensor and the neck-worn sensor design of their choice. Participants were then asked to perform a sequence of activities (see Table I) that may affect their level of privacy, perceived stigma, and comfort. They were requested to take notes in a diary while out in the field, and carried an explanation card to hand to strangers asking about the devices.

Participants then took 2-4 hours performing activities of their choosing to capture a wider variety of activities.

TABLE I
STRUCTURED ACTIVITIES THAT THE PARTICIPANTS DID FOR THE FIRST HOUR

Walk (Michigan Ave)	Observe peopleâĂŹs reaction, ask a stranger for directions.
Eat (home/restaurant)	Order/cook meal and eat
Go to coffee shop	Order a cup of water and drink
Go to bathroom	Use restroom turning off and removing the camera before going in, and turning it back on when coming out.
Check email	Write an email saying hello in the subject line to rawan.alharbi@northwestern.edu covering or turning off the camera before entering password information
Go to an ATM	Check account balance covering or turning off the camera before entering the password
Look at a mirror	Look at reflection from head to toe

After returning to the lab, they were asked to try on the other two video camera designs for 10-15 minutes while performing the following activities around the lab: walk to the super market, check email, eat a snack, and look at yourself in the mirror. They were then asked to complete a survey to measure the effect of each design on privacy, perceived stigma, and comfort. The participants were then instructed to review the recorded video for each camera design using DAT tools, delete any part of the video they did not want anyone to see, and annotate the eating episodes. After viewing their recorded video, they repeated the questionnaire to assess whether perceptions had changed. Participants were then asked to rate DAT ease of use.

Post-study, participants ranked the camera designs' wearability, and answer a new set of questions related to data privacy, stigma and willingness to wear the devices (paid or unpaid). As the participants were viewing their videos and answering survey questions, the research coordinator was monitoring participant response remotely and prepared questions and clarification for the participant's final interview phase.

D. Group Comparisons

Survey results were compared according to normal vs overweight vs obese, as well as male vs female using Welch's t-test, which is more reliable when the samples have unequal variances and sample sizes.

IV. Findings and Discussion

A. Demographics

The study comprised 13 participants (6 obese, 8 female, mean age 32.8 yrs, std 12.5). 6 participants exhibited at least one of these problematic eating episodes: emotional eating (n=5), hedonic eating (n=5) and a high likelihood of binge eating (n=6). All participants used social media, and 63.6% reported they are at least somewhat private in sharing information.

B. Participants' Concerns About Bystander Reactions

1) Video Camera: Participants expressed pre-study concerns to wearing the video camera, especially related to explaining it to bystanders reacting to being videotaped. One participant reported: "I was mostly concerned that other people I interacted would have privacy issues and ask me questions and I wouldn't know how to explain." The same participant later reported that "it got more comfortable as the day went on and I didn't really mind it as much especially since most people didn't really seem to be bothered by the camera." Participants asked about the video camera by bystanders who knew them (23%) either explained the details of the research or provided them with a research explanation card as instructed. No phone calls or concerns from bystanders were received by the research coordinator. Participants reported that they were asked questions about the scope of the footage and if the camera records audio.

2) Neck-worn device: One female participant who had participated in a study using neck-worn sensors before was concerned that the neck-worn devices would be "too heavy and obvious." At first, one male participant selected the throat microphone (N6), but after wearing it felt uncomfortable because it was too tight on him to wear all day, so he selected the black velvet choker (N3) instead. He thought by selecting the second design he would get attention from more people. However, he reported being less concerned after performing the experiment. Most people are too preoccupied with themselves, he reported: "People in Michigan Avenue didn't really have time to pay attention... I was worried they would look at me, but they didn't even notice."

One participant reported her coworker did not even recognize the neck-worn device as a smart device, thinking it was merely jewelry, owing to the board placement behind the neck.

TABLE II
MEASUREMENTS USED IN ADHERE-EAT EXPERIMENT

Stage	Measurement	Source	Type (# of Qs)
1	Emotional Eating	13-item Emotional Eating Sub-scale of the Dutch Eating Questionnaire [19]	Likert scale (13)
1	Impulsive Eating	StunkardâĂŹs Three Factor Eating Questionnaire [20]	True or False (29) and Likert scale (14)
1	Hedonic Eating	Power of Food Scale (PFS) [21]	Likert scale(13)
1	Binge Eating	Binge Eating Disorder Screening (BEDS-7) [22]	Yes or No (2) and Likert scale (5)
1	Privacy Attitude	Privacy Attitude Questionnaire (PAQ) [23] sub-scales: exposure, willingness to be monitored, interest in protection and willingness to share personal information.	Likert scale (36)
1, 4	Social Media Privacy Settings	iWatch Exit survey (General Section) [8]	Likert scale (1)
4-6	Wearables Privacy, Stigma and Comfort	Adapted from the iWatch Exit Survey [8]	Open-ended (47) and Yes or No (30).
5	Video and Annotation Ease of Use	This survey is designed to measure participant privacy concern change post-viewing of their video and the ease annotating start/end eating moments	Yes or No (2), Likert scale (1) and Open ended (3).
6	Data Privacy and Disclosure	Adapted from FieldStream Post-Report Privacy Questionnaire [14]	Likert scale (79)
6	Wearables Stigma	Selected questions from the stigma scale for mental illness [24] were adapted to measure stigma cause by each wearable.	Likert scale (7), for each device
6	Willingness to wear	Developed to measure participant willingness to wear in days if paid or not. It also captures participant barriers and facilitators to wearing devices.	Open ended (9)

3) Wrist-worn device: No participant reported any pre-concerns with wearing the mBand 2 wrist-worn device. One participant reported: "The wrist-worn device was pretty normal. Many people wear fitbits and other similar devices, so it's not really a big deal in terms of being self-conscious".

C. Disclosure of Eating Data

In discussing preconceived privacy concerns of participants, there was a clear difference between people who were overweight compared to people who were of normal or obese BMI. In response to reporting when participants over- or underate, overweight participants were significantly more concerned than others (t=2.09, p = 0.049), and the same is true regarding reporting the number of eating episodes per day(t=4.1, p = 0.032), suggesting a challenge in self-report for overweight participants over other participants. Figure 4 reports participant concern (on a Likert scale of 0-5) of reporting eating-related information. In reporting privacy concerns related to disclosure of identity to different groups, obese participants were more concerned with reporting to the public than any other group, while overweight participants were more concerned with reporting data to family and friends, suggesting the potential benefits of incorporating a role for family in weight interventions for obese participants, but not necessarily for overweight participants. The majority had no issue reporting data to researchers, doctors, and trainers/dieticians. One overweight participant reported: "I don't think I have very normal eating habits so I would feel embarrassed to have people know how often and how much I am eating. However for if it is for research and I know it will remain mostly private and confidential, I feel more at ease".

D. Privacy Management

71% of the participants said that they took off or turned off the camera in situations other than the use of ATM or bathroom. One participant was asked to take off the camera when volunteering at a school around students, and a few covered or took off the camera before approaching a private matter (e.g. talking to the doctor, inputting devices pass-code). There were no privacy concerns expressed in regards to the wrist-worn and neck-worn sensor.

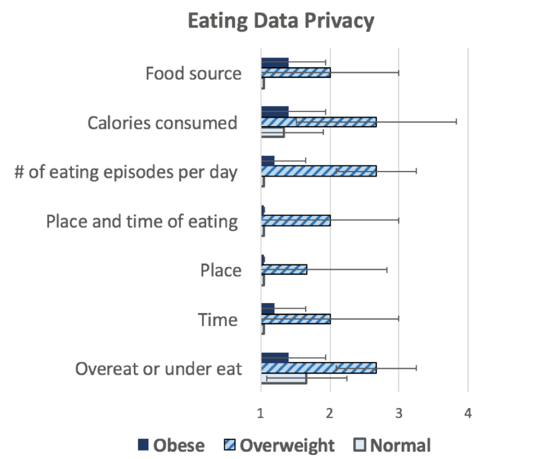

Fig. 4. Mean of each privacy concern in sharing eating data that can be captured by passive sensors or cameras. 1: Not at all | 2: A little concerned | 3: Moderately concerned | 4: Concerned | 5: Extremely concerned

E. Perceived Stigma

1) Stigma Associated with Criminality: Three participants were concerned the video camera on the shoulder or chest might be mistaken for a bomb. They were concerned the police might stop them. One participant said: "As a person of color, having a package attached to my arm and a coat, may look suspicious. I was worried police would stop me."

2) Stigma Associated with Environment: Participants have reported that it is very normal to wear a wrist band or an activity tracker, and reported that people did not react toward the camera because the test was done in a metropolitan area (downtown Chicago), where people are used to seeing a large variation in peoples' styles. Participants did feel, though, that these devices would garner further stigma in environments with less diversity.

F. Participant Comfort

Eight participants reported scenarios where the camera caused discomfort, one participant reported discomfort wearing the throat microphone, and three participants reported discomfort from the wrist-worn.

Participants responses were coded in order to understand what makes a wearable design comfortable. For the neck- and wrist-worn sensors, the design needed to 1) match their clothing or allow customization; 2) look like existing popular commercial wearables; or 3) be aesthetically pleasing; 4) be easy to adjust; and 5) be stable on the body.

As for the video camera, participants wanted control over the camera by being able to take it off or cover it without removing the harness. The video camera should feel secure on the body to allow for any kind of movement without throwing off their center of gravity (e.g. while running). Some participants mentioned preferring a video camera design that does not stand out, having it embedded as part of a t-shirt, necklace or wrist band. With the video camera, participants felt concerned about discussing the camera with others or obscuring its field of view when interacting with other people. Some participants felt it awkward or suspicious if others found out they were wearing a hidden video camera. However, it felt more acceptable to participants if the camera was hidden and only captured the wearer's face.

G. Motivation to Adherence

When asked, 82% of the participants agreed to wear the wrist- and the neck-worn sensor for 30 days if paid \$100. 82% were also willing to wear the entire system for 30 days if paid \$100 and were able to keep the equipment at the end of the study.

Figure 5 shows the coded motivators for wearing the devices. Obese participants were inclined to wear the device for more days if paid or if it could help them become healthy, perhaps showing hope that such a device could help them maintain or lose weight.

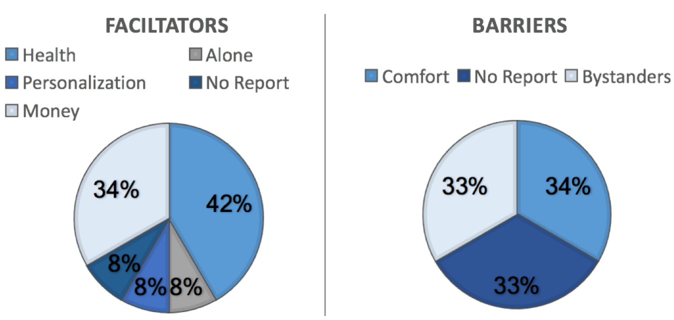

Fig. 5. Facilitators and barriers to adherence

H. Neck-worn Device Selection

More females than males were open to wearing the neck-worn sensor (3 females and 1 male selected N1, 1 female selected N2, 4 females selected N3, 4 males and 1 female selected N6 and no one selected N4 or N5), and generally the females preferred the jewelry-based or sport necklaces, while the males preferred the throat-microphone version.

I. Ranking Video Camera System

When asked to rank the video camera system they would be willing to use for a two-week study, the wrist camera was the winner (as first choices, cameras ranked 43% wrist, 29% shoulder, 21% chest, and 7% chose none). Five participants said they would not wear the chest camera. More men than females preferred the wrist camera. Women are more used to wearing chest undergarments possibly making then more accustomed to the feeling of a chest strap. The participants that selected the wrist camera selected it because it is hidden and people can control the camera field of view better than other designs. Participants who selected the chest camera as their first choice selected it because they thought that the weight was more evenly distributed and that it was less obvious than the shoulder camera; which they felt would draw more attention. The participants who reported the shoulder camera as their first choice selected it because they felt either that it weighed less than the chest camera, perhaps because the weight rested more on the shoulder; or that its video footage was best for privacy; or it was easier to wear.

J. Feasibility of Characterizing Eating Episodes

Table III summarizes the feasibility of each video camera design in capturing eating and non-eating related features in obese and non-obese participants averaged across 2 people trained in video labeling. The shoulder camera and the chest camera provide the greatest detection in eating-related gestures. The shoulder camera yields clearer sounds of chewing and swallowing, but overall the chest camera was slightly better in capturing the context of eating and non-eating. The shoulder camera outperformed the chest camera with obese participants due to the challenge of placing their chest cameras in a stable position. The wrist camera would rarely capture chews and never swallows, but outperformed other designs in identifying food quantity and type consumed.

For two participants (obese females) the chest camera proved difficult to identify any of the eating features since the camera was covered by the participant's jacket or table whenever the participant leaned forward to eat the sandwich. Some of the participants ate with their non-dominant hand, which made it challenging to capture with their wrist-worn sensor.

K. Labeling Data

1) Participant Annotation of Data: Participants were able to find and annotate 98% of their meals using the DAT system, particularly from video recorded through the chest and shoulder cameras. Participants reported difficulty labeling eating moments from the wrist video camera due to the rapid change in orientation due to the continuous motion of the wrist sensor. One participant reported feeling "disoriented," as she kept tilting her head as the orientation of the video was changing, which may cause strain in their neck over time.

2) Cues Aiding Participant Labels: Some participants remembered roughly the time that they ate in that day and then navigated to the predicted hour in the video. Others relied on sequence cues; they remembered that they ate after doing a particular activity (like shopping) or before going to the bank. Others used context cues like logos and music to identify their location to decide whether they ate there or not.

3) Drinking Labels Prove Challenging: Drinking moments were difficult to label as they occurred sporadically throughout the day. One participant would take one or two sips throughout the day, making it difficult to locate by glancing through the recorded video. Real time machine learning models may aid in providing cues for episodes of drinking.

		Frequency: Always(5) → Never(1)		
		Chest O|NO	**Shoulder O|NO**	**Wrist O|NO**
Eating	**Feeding Gestures**	3.0|5.0	4.6|5.0	4.7|4.7
	Chew	4.0|4.9	4.5|5.0	1.7|3.9
	Swallow	2.0|2.5	2.1|3.0	1.0|1.5
	Bite	4.0|5.0	4.8|5.0	4.5|4.7
	Food type	3.0|4.5	3.0|4.2	3.6|4.8
	Food amount	3.0|4.8	3.1|4.3	3.6|4.8
Average		**3.2|4.5**	**3.7|4.4**	**3.2|4.1**
Non-Eating	**Confounding Gestures**	3.5|4.6	5.0|5.0	5.0|5.0
	Social Interactions	3.0|4.9	4.1|4.5	4.8|4.8
	Media Screen	3.0|4.9	4.1|4.2	4.6|4.8
	Environment|Location	3.5|4.8	4.8|5.0	4.8|4.7
Average		**3.2|4.8**	**4.5|4.6**	**4.8|4.8**
Combined		**3.2|4.6**	**4.0|4.5**	**4.1|4.6**

TABLE III
FEASIBILITY OF EACH CAMERA DESIGN IN CAPTURING ACTIVITY. (O = OBESE, NO = NOT OBESE)

V. CONCLUSIONS AND LIMITATIONS

This paper presents initial steps in understanding barriers and facilitators to wearable adherence in research, especially wearable cameras and neck- and wrist-worn sensors. These findings suggest that participants manage their privacy by covering, removing or turning off the camera rather than deleting video segments. Customization, size, attachment, ease of wear and aesthetics are factors that can affect wearables comfort which greatly impacts adherence. It also suggests the importance of money and improving participant health as facilitators to wearables' adherence. Also, Perceived stigma regarding wearables may be greatly affected depending on the ethnic group studied and their environment. Although the majority of the participants prefer the wrist-worn camera, shoulder camera benefits in detecting specific eating gestures like the number of swallows and chews, and a wrist-worn video camera proves to be more successful in detecting non-eating activities. Findings also show significant challenges in self-reporting data from overweight compared to obese and normal BMI individuals, highlighting another reason to move to passive, objectively-measured eating behaviors.

This study comprised 13 participants who were predominantly women over 5 hours during daytime. In a future study, we hope to incorporate a greater number of individuals wearing the devices for a longer period of time, to capture other barriers and facilitators to wearables in eating-related research.

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