Mobile Ecological Momentary Diet Assessment Methods for Behavioral Research: Systematic Review

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Abstract

**Background:** Mobile device-assisted ecological momentary diet assessment (mEMDA) is a dietary assessment method that has not yet been optimized and has potential to minimize recall biases and participant burden while maximizing ecological validity. There have been limited efforts to characterize mEMDA methods used in behavioral research settings.

**Objectives:** The goals of this systematic review were to summarize the event-contingent and signal-contingent mEMDA approaches used in research to date, to characterize key aspects of these assessment approaches, and to discuss the advantages and disadvantages of each approach as well as implications for future mEMDA research.

**Methods:** Studies that used mobile devices and mEMDA methods to assess dietary intake were included. Data were extracted according to Preferred Reporting of Systematic Reviews and Meta-Analyses and Cochrane guidelines then synthesized narratively.

**Results:** The review included 20 studies (10 [50%] using event-contingent mEMDA and 10 [50%] using signal-contingent mEMDA). A majority the study methods (12, 60%) used mobile phones to collect dietary data. Event-contingent mEMDA methods most commonly assessed diet in real-time, used dietary records for data collection (6 studies, 60%) and provided estimates of energy and nutrient intake (6 studies, 60%). All signal-contingent mEMDA studies used a near real-time recall approach with unannounced (i.e., random) abbreviated diet surveys. Most signal-contingent studies (7 studies, 70%) summarized the frequency with which (targeted) foods or food groups were consumed. Relatively few (6 studies, 30%) studies compared mEMDA approaches with traditional dietary assessment approaches.

**Conclusions:** mEMDA approaches each have unique strengths and limitations that potentially impact the quality of reported dietary intake. Based on these early studies, focus needs to be on standardizing mEMDA approaches with the goal of maximizing data collection ecological validity and reliability while minimizing participant burden.
Key words: diet surveys, diet records, mobile phone, mobile applications, ecological momentary assessment
Introduction

Diet plays significant direct and indirect roles in the etiology and prevention of chronic diseases, including type 2 diabetes, coronary heart disease, cancer, and obesity. It has been estimated that an unhealthy diet was the leading cause of premature death in the U.S. contributing to more than 500,000 deaths in 2016 [1]. Despite these statistics, we lack a better understanding of how patterns of dietary intake affect health through the lifespan due to dietary measurement limitations. Current dietary assessment methods, including 24-hr dietary recalls, food frequency questionnaires, and manual and assisted dietary records, can be burdensome and are highly prone to recall biases and misreporting [2]. Research shows that people pay little attention to when and what they eat [3] and factors such as age, sex, and weight status can influence the accurate recall of food and estimation of portion size [2, 4-8]. Further, methods that do not use unannounced recalls (eg, dietary records) may be prone to biases such as psychological reactance or social desirability, which may lead to underreporting or omission of foods or beverages consumed or changes in usual dietary behaviors [9]. Errors in reporting, such as these, are known to have detrimental impact on studies investigating associations between diet and obesity or disease outcomes [10, 11]. Furthering our understanding of the links between diet and disease will require improvements in the dietary assessment methodologies. For this reason, the research community has recognized the need for new dietary assessment methods that can reduce misreporting and recall biases [12, 13].

Advancements in digital technology and computational sciences have catalyzed the development of new dietary assessment solutions aimed at automating the assessment of dietary intake. Dietary research has been dominated by two emerging assessment approaches: image-assisted and image-based assessment [14-24] and the detection of food intake by biomechanical sensors or hand-held devices [25-42]. Significant progress has been made in image-assisted and image-based food recording that has resulted in the improved accuracy of
dietary self-report [15, 24]. Similarly, wearable technology including gyroscopes, microphones, and mechanical or electrical impedance sensors have been adapted to detect wrist or hand motion [25-31] or patterns of chewing or swallowing indicative of food intake (eg, number of bites) [32-41]. However, design and proof-of-concept data suggest the automation of dietary assessment remains out of reach for the time being. For instance, the mean detection accuracy of image detection and wearable devices have been acceptable in controlled settings (range = 73-99%) [18, 26, 30, 31, 34, 35, 38-48] but limited testing has been done in natural settings [27]. The use of mechanical sensors in research is further hindered by poor battery life, having to remember to wear or use the device, needing to turn the device on or off to avoid detection errors, and the conspicuousness or general discomfort of having to wear collars, wires, or harness accessories. Substantial work will be needed before these methods can accurately quantify energy or nutrient intake for research purposes. Therefore, novel dietary assessment methods that reduce participant burden, recall biases and technological barriers, are needed [12, 13].

A third, less developed approach with the potential to improve the validity and reliability of dietary assessment is the mobile device-assisted ecological momentary assessment (mEMA). mEMA is based on the foundation of ecological momentary assessment (EMA) described by Shiffman and colleagues in 2008 [49]. EMA involves the repeated sampling of a person's current behaviors and experiences in real time, in their natural environments. Currently there are two mobile device-assisted ecological momentary diet assessment (mEMDA) approaches: event-contingent mEMDA and signal-contingent mEMDA. Event-contingent mEMDA most often occurs in real-time at the time of eating (or drinking). The frequency of sampling is determined by the number of times a participant reports eating. Here, the act of initiating a meal or snack triggers either the real-time recording of dietary intake (eg, dietary record) or an image-assisted dietary record. Image-assisted and image-based dietary records involve taking images of all foods and beverages to be consumed in real-time using the digital
camera housed within a mobile phone. Time-stamped images may be taken and processed through a mobile app or stored for download or transmission to a remote server where, at a subsequent time, the images can be processed for identification and amount using automated systems, dietitians or research staff, or they are used by study participants to enable a more accurate recall of foods eaten. The advantage of real-time diet records, with or without images, is these approaches are intended to capture all foods and beverages consumed without having to recall the events at a later time. While this is an advantage, the key limitation of event-contingent mEMDA is that there are no unannounced sampling events. The self-monitoring of dietary intake can be influenced by psychological factors that introduce measurement bias [5]. Furthermore, with image-assisted diet records, there is the potential for data entry bias by research staff viewing images or for misreporting errors (eg, inaccurate portion sizes) by participants, particularly if images are not taken at multiple points of a meal (eg, before and after a meal).

Signal-contingent mEMDA relies on signaled prompts to study participants that trigger the recall of recent dietary intake. While study participants are often prompted multiple times per day, signal contingent mEMDA does not always allow for the real-time assessment of dietary intake. Rather, assessment surveys often include questions referencing dietary intake occurring within the most recent interval of time (eg, past 30 minutes). Also, study participants are most often asked to report the consumption of specific foods or foods from specified food groups (eg, fruits and vegetables) by means of a brief survey. The frequency of sampling using signal-contingent mEMDA is determined by the researcher and can occur randomly at fixed or semi-fixed times, or randomly within fixed or semi-fixed time intervals. As with image-assisted or image-based dietary records, these momentary dietary assessments can be time-stamped and are either stored or transmitted for later database integration. While this method benefits from random (unannounced) sampling, short recall intervals, and reduced participant burden, the
typically used sampling schemes, limited study durations, or limited food lists can hinder the quantification of energy or nutrient intakes.

Due to recent advancements made in mobile device hardware and software and the pervasive use of mobile devices, EMA approaches leverage the capabilities of mobile technology, offering researchers an opportunity to assess the dietary intake of study participants as they are occurring in natural settings. Both event-contingent and signal-contingent mEMDA seek to reduce recall bias and thereby improve the accuracy of dietary assessment by eliminating or shortening the recall interval. However, neither approach has been well characterized nor compared against objective biomarkers or other methods of dietary assessment (e.g., doubly labeled water or 24-hour dietary recalls). Focused efforts are needed to develop mEMDA approaches for their consistent and replicable application in research settings. Therefore, the goals of this systematic review were to summarize the event-contingent and signal-contingent mEMDA approaches that have been used in research to date, to characterize key aspects of these assessment approaches (e.g., design, data collection methods, data processing and dietary analysis, and dietary outcomes), and to discuss the advantages and disadvantages of each approach as well as implications for future mEMDA research. The focus of the review was on studies using mobile devices to facilitate event-contingent or signal-contingent EMA methods to assess dietary intake.

Methods

Literature search

Six authors (SMS, YL, MDH, JH, CGD, CT, and CJB) devised systematic strategies to search the MEDLINE, EMBASE, PubMed, PsychInfo, and IEEE explore databases for all relevant literature published through February 2018. Searches were limited to articles written in the English-language and conducted with humans. Database search strategies included the use of
controlled vocabulary and keywords to identify studies addressing dietary assessment, mobile devices, and ecological momentary assessment. Keywords included “nutrition assessment”, “diet surveys”, “diet records”, “energy intake”, “meals”, or “eating” combined with “text messaging”, “mobile phone”, “mobile applications”, “micro-electrical-mechanical systems”, or “wearable electronic devices” were included as MeSH search terms. Additionally, non-MeSH search terms were included to be complete: “caloric intake”, “food diary”, “diet monitoring”, “food tracking”, “diet tracking”, “diet assessment”, or “calorie tracking” and “text messages”, “cell phone”, “smartphone”, “tablet computer”, “mobile health”, “eHealth”, “mHealth”, “digital health”, “mobile technology”, or “experience sampling”. References cited in all included studies and studies citing included studies were also reviewed to identify any additional studies.

**Study inclusion and exclusion criteria**

Eligible studies included those using mobile devices and event-contingent or signal-contingent EMA methods to assess dietary intake in research settings. Dietary intake was defined as the quantification of energy intake, macro- or micronutrients, or discrete foods, servings, or food groups. Studies were excluded if the described methods (i) were not used to assess diet in research (eg, proof-of-concept or technology design papers), (ii) were interventions with non-EMA dietary assessment methods (24-hour dietary recalls, food frequency questionnaires), (iii) did not assess dietary intake (e.g., binge eating lapses, availability of snack foods, food craving), (iv) used self-monitoring approaches without dietary analysis, (v) were described in an earlier study or were considered a secondary analysis, or (vi) were not peer-reviewed journal articles (e.g., abstracts, editorials, discussions, evaluations, reviews, reports, news, notes, surveys, or content analysis). Additional papers referencing the included studies were used to obtain methodological details not otherwise provided in the included studies.

**Data extraction and analysis**

Data were extracted into a structured coding form according to PRISMA (Preferred Reporting of Systematic Reviews and Meta-Analyses) guidelines [50] and the Cochrane Handbook for
Systematic Reviews of Interventions [51]. Four authors (SMS, YL, SES, and KGH) independently extracted and reviewed characteristics from all studies using a data extraction form developed for this review. Extracted data represented details on mEMDA methods and included, but was not limited, to: (i) mobile platform, (ii) sampling duration, (iii) prompt approach (signal-contingent only), (iv) prompt frequency (signal-contingent only) (v) data collection method, (vi) data processing and nutrient analysis, (vii) diet data outcomes. A list of data extracted from included studies is provided as Multimedia Appendix 1. Discrepancies in the extracted data were resolved by a discussion between the expert reviewers (SMS and YL) to complete the dataset. In several cases, studies closely related to the included studies were reviewed for additional information to resolve issues of missing or unclear data. Extracted data were descriptive in nature. The data were synthesized narratively and tabularized with the intent of summarizing available methods for assessing diet using mobile EMA approaches.

Results

Literature Search

The literature search yielded 1,462 studies, of which 173 were duplicates, leaving 1,289 articles to be screened for eligibility. A total of 463 articles were excluded based on an initial screening indicating these were not journal articles. Thus, 826 articles were screened by title, abstract, and methods for eligibility. After 806 articles that did not meet the inclusion criteria were excluded, 20 studies were included in the review (see PRISMA diagram, Figure 1). An additional 19 journal articles were used to obtain methodological details not provided in the included studies.
Figure 1. PRISMA diagram

Records identified through database searching
n=1448

Additional records identified through other sources
n=14

Total records retrieved
n=1462

Duplicate records excluded
n=173

Records excluded
n=463
- Abstract, n=278
- Review, n=120
- Editorial, letter, news, note or survey, n=62
- Content analysis, n=2

Records screened by article type
n=1289
**Summary of event-contingent studies**

The methods in articles using event-contingent mEMDA approaches are summarized in Table 1. A total of 10 studies described event-contingent mEMDA methods used in nutrition-related research [52-61]. Additional approach details were extracted from other related journal articles [43, 62-73].

**Design:** Of the 10 studies, 5 were mobile phone-based [53, 57-59, 61]: 3 used mobile phone apps [53, 57, 61] and 2 used the mobile phone camera function (57, 59). The remaining 5 studies used a PDA device with customized software [55, 60], an Internet-based app [52, 54], or social media (Twitter) [56]. All studies assessed dietary intake continuously throughout each day. The sampling duration ranged from 3 days to 3 months with 6 days being the most common.

**Data collection methods:** Six studies collected data by dietary records [52, 54-56, 58, 60]. One study used a note-taking app with image capture (52). Others had study participants record the consumption of pre-defined food types or food groups [54-56, 58, 60]. Three studies had study participants take images of all food and beverage consumed without additional note-taking [53, 57, 61] and 1 study collected dietary data by voice-annotated video taken with a mobile phone [59]. One study provided all food and beverage to participants to take home during the study period and encouraged them to supplement with usual foods and beverages not provided [53]. All other studies collected dietary data based on a participant’s usual eating behaviors. Hingle and colleagues [56] collected 1,756 food-related hashtags via Twitter across all participants over 3 days. In Seto and colleagues’ [59] 6-day study, 72 food items were reported via video per participant. Participants on average reported 7 food entries via dietary record per day in Ashman and colleagues’ 3-day study [52]. Two studies used alternative methods to capture missed meals (ie, pen-and-pencil or voice recording). One study used EMA prompts at standard or usual breakfast, lunch, dinner, and snack times as a reminder to log eating events [57].
**Dietary analysis and outcomes**: Five studies involved trained dietitians or research staff to analyze the data based on a nutrient database or software [52, 53, 57, 59]; 3 studies downloaded data from the mobile device to perform further data analysis without the use of a nutrient database or software [55, 58, 60]; 2 utilized output generated by non-nutrient-related software or app [54, 56], and 1 automated the nutrient analysis within the study app [61]. With respect to the primary outcomes assessed, 5 studies estimated energy intake [52, 53, 57, 58, 61]. Four studies estimated macro- or micronutrients [52, 53, 57, 61]. Two studies estimated portions or servings consumed from designated food groups [59, 60]. Four studies provided dietary data at within day level (i.e., for each meal) [56, 58, 59, 61]; the remaining studies provided dietary data summary at the day level.

**Protocol adherence**: Protocol adherence was not provided in any of the event-contingent studies. However, 3 studies reported the number of eating events captured or frequency with which foods were consumed [52, 56, 59].

**Comparison testing**: Four studies compared mEMDA methods against a standard method [52-54, 57]. Two compared estimated energy intake with doubly labeled water [53, 57]. Martin and colleagues [57] found no significant difference in energy intake between the estimation from their mEMDA method (Remote Food Photography Method) versus the doubly labeled water in a sample of overweight and obese adults. However, in another comparison test related to the mEMDA method used by Martin and colleagues, Nicklas and colleagues [63] found the Remote Food Photography Method underestimated energy intake when compared to doubly labeled water by an average of 222 kcal/day in a sample of minority (Hispanic and African American) pre-school children (data reported by their caregivers). In Boushey's study [53] the mean percent of underreporting was 12% for men (SD ± 11%) and 10% for women (SD ± 10%). Two compared estimated intake to 24-hour dietary recalls [52, 54]. Della-Torre and colleagues [54] found the primary diet data had greater than 85% agreement with the 24-hour dietary recall
while Ashman and colleagues [52] found the macronutrient and energy intake had greater than 90% agreement with the 24-hr dietary recall.
<table>
<thead>
<tr>
<th>First author, year</th>
<th>Mobile Platform</th>
<th>Sampling duration</th>
<th>Data collection *</th>
<th>Data processing and nutrient analysis</th>
<th>Diet data outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashman, 2017 [52]</td>
<td>Internet-based app</td>
<td>3 days</td>
<td>Image-assisted dietary record: images taken before and after meals with fiducial marker</td>
<td>Dietitians analyzed food images with FoodWorks software</td>
<td>Energy, protein, dietary fat, carbohydrates, and select micronutrients</td>
</tr>
<tr>
<td>Boushey, 2017 [53]</td>
<td>Mobile phone app</td>
<td>7.5 days</td>
<td>Image-assisted dietary record: images taken before and after meals with fiducial marker</td>
<td>Trained analysts analyzed food images with Food and Nutrient Database for Dietary Studies</td>
<td>Energy intake</td>
</tr>
<tr>
<td>Della-Torre, 2017 [54]</td>
<td>Internet-based app</td>
<td>4 days</td>
<td>Dietary record: food and beverages chosen from 900 options</td>
<td>Automated app output (study-specific food composition database)</td>
<td>Energy, protein, dietary fat, carbohydrate, fruit and vegetables, dairy</td>
</tr>
<tr>
<td>Grenard, 2013 [55]</td>
<td>PDA software</td>
<td>7 days</td>
<td>Dietary record: food and beverages chosen from 3 groups</td>
<td>Data downloaded from PDA by researchers (no nutrient database used)</td>
<td>Number of sweetened drinks, sweet snacks, salty snacks, and sweet or salty snacks</td>
</tr>
<tr>
<td>Hingle, 2013 [56]</td>
<td>Social media (Twitter)</td>
<td>3 days</td>
<td>Dietary record: food and beverages chosen from 24 groups</td>
<td>Web-based data capture app (VIBE) used to automatically calculate output (no nutrient database used)</td>
<td>Number of times each food category was reported</td>
</tr>
<tr>
<td>Martin, 2012 [57]</td>
<td>Mobile phone app</td>
<td>6 days</td>
<td>Image-assisted dietary record: images taken before meals with fiducial marker</td>
<td>Image analysis by 2-step process: human raters and computer automation with Food and Nutrient Database for Dietary Studies</td>
<td>Energy, protein, dietary fat, carbohydrates, and select micronutrients</td>
</tr>
<tr>
<td>Schuz, 2015 [58]</td>
<td>Mobile phone app</td>
<td>10 days</td>
<td>Dietary record: items labeled as breakfast, lunch, dinner, snacks, and drinks</td>
<td>Data downloaded from app by researchers (no nutrient database used)</td>
<td>Frequency of meals, snacks, non-alcoholic drinks, or alcoholic drinks</td>
</tr>
<tr>
<td>Seto, 2016 [59]</td>
<td>Mobile phone</td>
<td>6 days</td>
<td>Voice-annotated video with time-stamp</td>
<td>Dietitians analyzed the videos and coded the portion size and food groups (no nutrient database used)</td>
<td>Portions of total meal, dairy, protein, gain, vegetable, and fruit</td>
</tr>
<tr>
<td>Thomas, 2011 [60]</td>
<td>PDA software</td>
<td>6 days</td>
<td>Dietary record: food and beverages chosen from 8 groups with manual entry of food type and portion size</td>
<td>Data downloaded from PDA by researchers (no nutrient database used)</td>
<td>Food group servings</td>
</tr>
<tr>
<td>Waki, 2014 [61]</td>
<td>Mobile phone app</td>
<td>3 months</td>
<td>Image-assisted dietary record: images taken before meals</td>
<td>Automatic photo processing by app (Dialbetics) software and Dietary Reference Intakes</td>
<td>Energy, protein, dietary fat, carbohydrate, dietary fiber, and sodium</td>
</tr>
</tbody>
</table>

Table 1. Event-contingent, mobile ecological momentary dietary assessment approaches

* All food and beverage recorded unless otherwise noted
Summary of signal-contingent studies

The methods in articles that only used signal-contingent mEMDA approaches are summarized in Table 1. A total of 10 studies described signal-contingent mEMDA methods used in nutrition-related research [74-83]. Additional approach details were extracted from multiple related journal articles [79, 84-89].

**Design:** Of the 10 studies, prompts were delivered via mobile phone in 7 studies [74-76, 79, 80, 82, 83]. Of these 7 studies, 5 used mobile apps [75, 76, 79, 80, 82], 1 used SMS text messaging [74], and 1 used a web-based survey [83]. Two other studies used a wrist-worn electronic diary device [77, 78] and another study used an iPod Touch [81]. Five studies used *random* intervals for prompting [75-77, 82, 83] with frequencies ranging from 3 to 10 prompts per day. Three of these 5 studies assessed dietary intake “since the last prompt” at varied time intervals [77, 82, 83], 1 study assessed dietary intake in the past 2 hours [76], and 1 study assessed dietary intake in real-time [75]. The other 5 studies prompted surveys at *fixed* intervals [74, 78-81], and frequencies ranged from 4 to 14 prompts per day. Two of these 5 studies assessed dietary intake “since the last prompt” at varied time intervals [79, 81], 2 studies assessed dietary intake in the past 1-3.5 hour(s) [78, 80], and 1 study assessed dietary intake in real-time [74]. The sampling duration for the 10 studies ranged from 4 days to 6 weeks, with the most common duration being 7 days (n=4).

**Data collection method:** All studies used an abbreviated survey format to collect dietary data. The number of diet-related survey items ranged from 1 to 9 items. Three studies chose their dietary variables from intake patterns specific to the targeted population [75, 80, 83]. One study chose the dietary variables from the USDA food pyramid [60]. One study provided a search function linked with a national food composition database within the study app [82]. The number of overall diet-related survey items ranged from 1 to 16 items.
**Dietary analysis and outcomes:** Response data were downloaded from the respective mobile platform by researchers to perform analysis without use of a nutrient database for all studies. Seven signal-contingent studies reported on the occurrence or frequency of (targeted) food or food group intakes at the day-level [74-76, 78, 80, 81, 83]. Three studies focused on snack intake only [78, 79, 83]. Only 2 studies estimated energy intake [79, 82]. Another study estimated servings of low glycemic index foods [77].

**Protocol adherence:** EMA prompt response rate was reported in 8 out of the 10 studies [74, 76, 77, 79-83]. Response rate ranged from 23-63% per day to 98% across the study period. The mean response rate across all studies was 79%.

**Comparison testing:** Two studies compared their mEMDA methods against 24-hour dietary recalls [75, 76]. In Bruening's study [75], the concordance rate at the day level ranged from 79% for entrees to 94% for fruit and vegetables in a sample of college students. In Dunton's study [76], the two-hour concordance rate ranged from 65% for fruits/vegetables to 90% for soda/energy drinks in a sample of children (mean age = 10 years) [87].
<table>
<thead>
<tr>
<th>First author, year</th>
<th>Mobile platform</th>
<th>Sampling duration</th>
<th>Prompt approach</th>
<th>Prompt frequency (recall interval)</th>
<th>Diet data collection (format, source)</th>
<th>Diet data output outcomes (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkman, 2014 [74]</td>
<td>Mobile phone SMS text messages</td>
<td>14 days</td>
<td>Individualized fixed time</td>
<td>4 prompts: 3 real-time, 1 retrospective (since last prompt)</td>
<td>1 survey item (open-ended, pre-selected snack food)</td>
<td>Frequency of snack intake</td>
</tr>
<tr>
<td>Bruening, 2016 [75]</td>
<td>Mobile phone app</td>
<td>4 days</td>
<td>Random interval</td>
<td>8 prompts: 7 real-time, 1 retrospective prompt (past 3 hrs)</td>
<td>2 survey items (multiple-choice, 8 food groups and 8 beverage groups)</td>
<td>Bread or grains, entrée, fruit and vegetables, salty foods, and sweets intake (number and percent of prompts)</td>
</tr>
<tr>
<td>Dunton, 2015 [76]</td>
<td>Mobile phone app</td>
<td>8 days</td>
<td>Random interval</td>
<td>Mother: 4 or 8 retrospective prompts (past 2 hrs)  Child: 3 or 7: retrospective prompts (past 2 hrs)</td>
<td>1 survey item (multiple-choice, 5 food groups)</td>
<td>Healthy and unhealthy eating (frequency of prompts)</td>
</tr>
<tr>
<td>Miller, 2016 [77]</td>
<td>Wrist-worn electronic diary</td>
<td>6 weeks</td>
<td>Random interval</td>
<td>3 retrospective prompts (since last prompt)</td>
<td>1 survey item (open-ended)</td>
<td>Low GI foods (servings)</td>
</tr>
<tr>
<td>Powell, 2017 [78]</td>
<td>Wrist-worn electronic diary</td>
<td>7 days</td>
<td>Fixed time (±10 min.)</td>
<td>14 retrospective prompts (past hour)</td>
<td>8 survey items (8 food groups, yes or no)</td>
<td>Snack and fruit and vegetable intake (ranked portion sizes)</td>
</tr>
<tr>
<td>Richard, 2017 [79]</td>
<td>Mobile phone app</td>
<td>7 days</td>
<td>Fixed time</td>
<td>5 retrospective prompts (since last prompt)</td>
<td>1 survey item (open-ended)</td>
<td>Snack intake density (kcal/100 g)</td>
</tr>
<tr>
<td>Spook, 2013 [80]</td>
<td>Mobile phone app</td>
<td>7 days</td>
<td>Fixed time (±30 min.)</td>
<td>5 retrospective prompts (past 3.5 hrs)</td>
<td>3 survey items (multiple choice and visual analogue scales, 3 food groups)</td>
<td>Number and frequency of snack, fruit and vegetable, and soda intake</td>
</tr>
<tr>
<td>Strahler, 2018 [81]</td>
<td>iPod Touch app</td>
<td>4 days</td>
<td>Fixed time</td>
<td>5 retrospective prompts (since last prompt)</td>
<td>3 survey items (multiple choice recoded to yes or no)</td>
<td>Frequency of meal type, main component, and drink consumption</td>
</tr>
<tr>
<td>Wouters, 2016 [82]</td>
<td>Mobile phone app</td>
<td>4 days</td>
<td>Quasi-random interval (avg. 90 min.)</td>
<td>10 retrospective prompts (since last prompt)</td>
<td>Digital food log of snacks (open-ended)</td>
<td>Energy intake carbohydrate, fat, and protein</td>
</tr>
<tr>
<td>Zenk, 2014 [83]</td>
<td>Mobile phone web-based survey</td>
<td>7 days</td>
<td>Random interval</td>
<td>5 retrospective prompts (since last prompt)</td>
<td>9 web-based survey items (9 food groups, yes or no)</td>
<td>Number of snacks consumed (0 or 1+)</td>
</tr>
</tbody>
</table>
Discussion

Summary of Key Findings

This systematic review summarized the existing methods for measuring dietary intake using two mEMDA approaches: event-contingent and signal-contingent mEMDA. Twenty studies were included in the review. Half of the studies used event-contingent and half used signal-contingent methods. Most studies used mobile phones to collect dietary data. Studies that used event-contingent mEMDA methods most commonly assessed diet in real-time, used dietary records to collect data, and provided estimates of energy and nutrient intake. All signal-contingent mEMDA studies, used near real-time recalls and unannounced abbreviated diet surveys, and summarized the frequency with which (targeted) foods or food groups were consumed. Only 6 (30%) mEMDA studies compared mEMDA outcomes to dietary outcomes measured by traditional dietary assessment methods (eg, doubly labeled water and 24-hr dietary recalls); however, results of these studies demonstrated good agreement between methods. As such, the evolving body of literature identified in this review supports the application of mEMDA methods as the next step for advancement in the field of dietary assessment, bridging the gap between traditional methods and newer, more technologically advanced methods (i.e., biomechanical sensing and image-based food detection) which are currently under development.

Key Strengths and Limitations of mEMDA methods

The mEMDA approaches described in this review have strengths and limitations potentially impacting the quality of estimated dietary intake. Event-contingent methods, used in n=10 of the reviewed studies, have several strengths. Studies that used event-contingent mEMDA methods most commonly assessed diet in real-time (vs. near real-time), used dietary records to self-report intake or used image-assisted or image-based approaches to lessen the reliance on self-report, and calculated estimates of energy and nutrient intake. Because food (and beverage) consumption generally occurs as a discrete event, it serves as a cue to record
intake [90]. This approach allows for assessment of an individual's complete dietary intake during measured days, assuming full compliance to the protocol. The automated time-stamp for each eating event removes some burden from participants, allows for better specificity for eating occasions, and enhances the ability to examine the distribution and frequency of eating events across days or weeks [90]. There are also several limitations inherent to event-contingent mEMDA methods. First, this approach requires participants to initiate the reporting of each eating event, which may be perceived as burdensome and may lead to omitted data when participants forget or decline to report, or extraneous data when participants input entries for eating events that did not occur [49]. Furthermore, the continuous self-report of dietary intake (vs. unannounced recalls) consistent with event-contingent mEMDA is more likely to be biased by psychological reactance or social desirability; whereby, people change their usual eating behaviors or intentionally misreport intake so not to be judged for making diet-related decisions perceived by the individual to be less healthful [5]. Finally, event-contingent methods tend to involve more high-resource data processing in order to analyze the raw food-level data for micro- or macro-nutrients and food group servings at the day- or meal-level, most commonly in the form of trained or specialized staff (e.g., dietitian). Overall, event-contingent mEMDA methods are useful for capturing individuals’ intake as it occurs, by eliciting a time-stamped log of all eating events and their contents; however, limitations include greater participant burden (ie, recording all food and beverage consumed and remembering to do so) and the increased likelihood of psychological reactance or social desirability biases.

The remaining studies (n=10) used signal-contingent mEMDA sampling. All of the signal-contingent mEMDA studies used a near real-time recall approach with abbreviated diet surveys, while some also incorporated real-time prompting. Most signal-contingent studies summarized the frequency with which targeted foods or food groups were consumed. Strengths of signal-contingent approaches include lower participant burden and unannounced sampling, which provides a random sampling of eating events throughout the day. Here, participants receive
prompts to report on their recent intake throughout the day, providing a representative sample of overall daily intake without having to proactively input details about each eating occasion as they occur. Additionally, the majority of existing signal-contingent studies used simplified reporting methods, asking participants whether or not they consumed certain target foods within a recent interval of time (eg, past 30 minutes, past 2 hours). Though this approach has several strengths, there are also limitations to note. First, signal-contingent mEMDA may be subject to incomplete data, particularly when sampling windows do not cover the entire day. As a result, some eating events may be omitted. Also, dietary intake captured by signal-contingent reporting is subject to lower specificity of timing, particularly when the recall window is longer (eg, >2 hours), as participants are typically asked to report whether or not food (or beverage) consumption has occurred, without elaboration about the specific time it occurred. Additionally, although existing signal-contingent methods have typically used lower-resource processing methods (eg, not requiring advanced training), the resulting data may be limited to frequencies of intake as opposed to estimates of energy intake or nutrients. To summarize, signal-contingent methods are able to capture a representative sample of individuals’ daily intake while minimizing the participant burden associated with participant-initiated reporting; however, this approach may not be suited for time-stamping eating events or quantifying dietary intake (ie, estimating energy or nutrient intake).

To date, the few studies that have compared mEMDA methods to standard method have generally found acceptable agreement. For instance, two studies that compared mEMDA reports of estimated energy intake against doubly labeled water [53, 57], found that mEMDA methods underestimated energy intake by an average of 222 kcal/day [63] and approximately 11% [53], respectively. Four studies compared event-contingent [52, 54] and signal-contingent recalls [75, 76] mEMDA estimated intake to 24-hour dietary recalls. Event-contingent studies demonstrated 85% agreement for primary diet data [54] and 90% agreement for macronutrient and energy intake [52], while signal-contingent studies found day-level concordance ranged
from 79% (entrees) to 94% (fruit and vegetables) in a sample of college students [75] and two-hour concordance ranged from 65% (fruits and vegetables) to 90% (soda and energy drinks) for children [76]. These promising preliminary comparison studies provide evidence that mEMDA approaches may be interchangeable with existing methods, however future studies should continue to investigate their comparability and reliability. By reviewing the literature and identifying key trends, strengths, and weaknesses of existing momentary diet assessment methods, a unique topic of high relevance in the dietary assessment community and EMA community, researchers may better understand and move forward with improving and incorporating mEMDA methods into their own research.

**Strengths and Limitations of the Current Review**

Our systematic review is the first to summarize the existing literature of mEMDA methods for the measurement of diet in research studies and to discuss corresponding strengths and weaknesses. This review was based on a comprehensive search across multiple domains (images, biomechanical approaches, EMA, etc.) using current guidance for a robust systematic review process. The current review was limited in breadth as a result of many burgeoning approaches not yet being applied in research settings and excluded from the present review. Additionally, due to the wide divergence of study measures and reporting of relevant items (eg, protocol adherence), we were only able to narratively describe data collection approaches. Furthermore, this review was not able to touch upon the ability of mEMDA approaches to capture diet compared to traditional methods of dietary assessment due to limited report of such method comparison statistics in existing studies.

**Implications for Future Research**

Currently, there is a need within the field of momentary diet assessment to maximize data quality while minimizing participant burden. Ecologically valid and reliable data on individuals’ dietary intake is essential to understand the role of diet on human health through the lifespan. Because of the known limitation of existing dietary assessment methods, the research
community is motivated to develop new solutions aimed at (semi-)automating the assessment of dietary intake. While the automated methods of real-time image-based detection [14-24] and real-time detection of food intake by biomechanical sensors or hand-held devices [25-42] have seen significant progress [15, 24] in terms of identifying foods and estimating portion sizes [14-24] detecting wrist or hand motion [25-31] or patterns of chewing or swallowing indicative of food intake, [32-41] the design and proof-of-concept data suggest the automation of dietary assessment remains out of reach for the time being. Given these limitations, mEMDA, characterized by the repeated assessment of an individual's behaviors and experiences in real- or near-real time in their natural settings, represents a novel dietary assessment method. Compared with traditional methods, mEMDA methods may reduce participant burden, recall biases and technological barriers while maximizing ecological validity. Therefore, mEMDA methods, have the potential to bridge the gap between currently available methods (eg, 24-hour dietary recall) and newer methods (e.g., biomechanical sensors) which are currently under development.

The strengths of event-contingent methods (eg, ability to capture the full-day of dietary intake and estimate energy and nutrient intakes) and of signal-contingent methods (eg, lower participant burden and unannounced prompting schemes) could potentially be leveraged to design novel mEMDA methods that reduce their individual limitations. Based on these early studies, efforts now need to be focused on standardizing mEMDA approaches with the goal of maximizing data quality and ecological validity while minimizing participant burden. Existing studies illustrate the wide range of dietary outcomes assessed through mEMDA methods, and although the ability to develop and tailor assessment items based on a particular study’s needs is an advantage, the divergence of outcome measures and lack of validation remains a major challenge.
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