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N-of-1 study of weight loss maintenance assessing predictors of physical activity, adherence to weight loss plan and weight change

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Objective: Behaviour change interventions are effective in supporting individuals to achieve clinically significant weight loss, but weight loss maintenance (WLM) is less often attained. This study examined predictive variables associated with WLM.
Design: N-of-1 study with daily ecological momentary assessment combined with objective measurement of weight and physical activity, collected with wireless devices (Fitbit™) for six months. Eight previously obese adults who had lost over 5% of their body weight in the past year took part. Data were analysed using time series methods.
Main outcomes measures: Predictor variables were based on five theoretical themes: maintenance motives, self-regulation, personal resources, habits, and environmental influences. Dependent variables were: objectively estimated step count and weight, and self-reported WLM plan adherence.
Results: For all participants, daily fluctuations in self-reported adherence to their WLM plan were significantly associated with most of the explanatory variables, including maintenance motivation and satisfaction with outcomes, self-regulation, habit, and stable environment. Personal resources were not a consistent predictor of plan adherence.
Conclusion: This is the first study to assess theoretical predictions of WLM within individuals. WLM is a dynamic process including the interplay of motivation, self-regulation, habit, resources, and perceptions of environmental context. Individuals maintaining their weight have unique psychological profiles which could be accounted for in interventions.

Keywords: behaviour change maintenance; n-of-1 study; theory; weight loss maintenance

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Introduction

Weight loss maintenance (WLM) has been defined as a process of sustaining a significant intentional weight loss accomplished by one's own efforts and/or as a result of treatment (Elfhag & Rossner, 2005). The specific criteria used to define WLM vary between research studies. Discrepancies include the percentage of weight loss required and the length of time for maintained weight loss. For instance in terms of percentage weight loss, WLM researchers suggest that a minimum of 3% (Stevens, Truesdale, McClain, & Cai, 2005), 5% (Crawford, Jeffery, & French, 2000) or 10% (Wing & Hill, 2001) is necessary to be classified as successful WLM. The time period requirements for substantial WLM also differ; for example, a minimum of 6 months (Elfhag & Rossner, 2005), 12 months (Wing & Hill, 2001) or 24 months (Stevens et al., 2005) of maintained weight loss have been suggested. Some studies classify people as successful in WLM on the basis of losing and maintaining a reduction of more than two body mass index points for at least a year and a half (Cuntz, Leibbrand, Ehrig, Shaw, & Fichter, 2001).

Many behavioural interventions are effective in achieving clinically significant weight loss (Dombrowski, Avenell, & Sniehott, 2010; Jolly et al., 2011); however, most of the weight lost is subsequently regained. Systematic reviews of interventions promoting an increase in physical activity and a healthy diet have reported that half of the initial weight loss was regained after one year (Curioni & Lourenço, 2005). A systematic review of the long-term effects of treatments for obesity reported that people regain a third of their initial weight loss within a year and the rest within 3–5 years (Avenell et al., 2004). A recent systematic review of WLM interventions showed that interventions focusing on dietary intake and physical activity are effective in slowing weight regain, but effects are modest and heterogeneous (Dombrowski, Knittle, Avenell, Araújo-Soares, & Sniehotta, 2014). A more intricate understanding of what makes some individuals successful in their WLM would help the design of WLM interventions by highlighting which variables need to be targeted.

Previous studies assessing predictors of WLM and sustainable behaviour change have employed between-participant designs (Svetkey et al., 2008; Wing & Phelan, 2005). However, long-term individual weight management may involve critical intra-individual changes which may be overlooked by these designs. Variables associated with healthy eating, being physically active, and following a WLM plan are theorised to vary within individuals. For instance, the availability of cognitive resources is hypothesised to moderate the likelihood of engaging in healthy behaviours (e.g. people are more likely to perform healthy behaviours when they are rested, relaxed, and when their attention span is at its best (Hofmann, Friese, & Wiers, 2008)). Assessing within-person differences has the potential to uncover important factors that impact on WLM (Sniehotta, Simpson, & Greaves, 2014).

Lately, within-person assessments of cognitions underlying health-related behaviours have been more commonly used in health psychology (Davidson, Peacock, Kronish, & Edmondson, 2014). The n-of-1 design is a recommended method for testing behavioural theory within individuals through repeated measures over a period of time (Craig et al., 2008). The main features of n-of-1 include the possibility to examine within-person variability in cognitions and outcomes, and to test theory within individuals (Johnston & Johnston, 2013). The n-of-1 design has been successfully used in various settings and to study various behaviours, including physical activity (Hobbs, Dixon, Johnston, & Howie, 2013; Nyman, Goodwin, Kwasnicka, & Callaway, 2016; Sniehotta, Presseau, Hobbs, & Araújo-Soares, 2012), and testing an integrated model of disability in individuals with chronic pain (Quinn, Johnston, & Johnston, 2013). To date, no studies have examined day-to-day variability in predictors of WLM behaviours.

This n-of-1 study examined predictors of WLM behaviours in individuals who had already successfully lost a clinically significant amount of body weight. In line with a systematic review of maintenance theories (Kwasnicka, Dombrowski, White, & Sniehotta, 2016), maintenance relevant theoretical predictors were measured to investigate their association with WLM plan adherence and with physical activity. The association between WLM plan adherence and weight was also examined. The aim of the study was to explore associations between the theoretical predictors of WLM and objective (physical activity) and subjective (WLM plan adherence) individual level outcomes.

Methods

Design

The study used an observational n-of-1 design with self-report measures of WLM-relevant theoretical variables. Dependent variables were: objectively estimated step count using Fitbit™ proprietary algorithms and daily weight, and self-reported WLM plan adherence. Predictor variables were based on five theoretical themes previously linked to behaviour change maintenance: maintenance motives, self-regulation, personal resources, habits, and environmental/social influences, described in further detail below.

Measurements

Ecological momentary assessment (EMA)

EMA utilised questionnaires, which were sent to participants twice a day (morning and evening), to assess theory-based predictors of WLM and WLM plan adherence (Table 1). In the morning, participants selected a suitable time between 6am and 10am; and in the evening, between 6pm and 10pm. Questionnaires were delivered automatically via text or e-mail depending on participants' preferences. All questions were answered on a 0–100 sliding visual analogue scale, apart from one (hours of sleep). Variables measured in the morning included views on WLM for that day: importance, motivation, confidence, and number of hours slept. Variables measured in the evening included retrospective reflections on the particular day: adherence to WLM plan, temptations, stress, energy levels, hunger, appreciation of weight loss benefits, social support, happiness, awareness, physical pain, obstacles, routines, and typicality of the environment. Participants had the opportunity to select additional personally relevant questions if they felt that there was another important variable that had not been included in the question list; e.g. 'How much did the weather influence your weight loss maintenance?' Question order within each set (morning and evening) was randomised daily for each participant. At the end of each questionnaire, participants could optionally provide additional free-text information on anything that influenced their WLM on that day or on anything else that related to the study (e.g. 'I had a friend's birthday party so I did not comply with my plan'; 'I forgot to wear my activity monitor'). All questionnaire

Table 1. Ecological momentary assessment questions and relevant themes.

Question wording	Theme
Morning questions	
How important is your weight loss maintenance plan compared to other things you want to do today? (0 – not important, 100 – very important)	Maintenance motives
How motivated are you to follow your weight loss maintenance plan today? (0 – not motivated, 100 – very motivated)	Maintenance motives
How confident are you that you can follow your weight loss maintenance plan today? (0 – not confident, 100 – very confident)	Self-regulation
How many hours of sleep did you have last night? (open ended question)	Resources
Evening questions	
How much have you followed your weight loss maintenance plan? (0 – not at all, 100 – completely)	Outcome variable
How tempted have you felt to break your weight loss maintenance plan? (0 – very tempted, 100 – not tempted at all)	Self-regulation
How stressed have you felt today? (0 – very stressed, 100 – not stressed at all)	Resources
How energetic have you felt today? (0 –not energetic, 100 – very energetic)	Resources
How hungry have you felt today? (0 – very hungry, 100 – not hungry at all)	Self-regulation
How much have you appreciated the benefits of your weight loss today? (0 – not at all, 100 –all the time)	Maintenance motives
How supported by other people in your weight loss maintenance plan have you felt today? (0 – not supported, 100 – very supported)	Environment
How happy have you felt today? (0 – very unhappy, 100 – very happy)	Resources
How aware were you of your weight loss maintenance plan today? (0 – not at all, 100 – very aware)	Self-regulation
How much physical pain have you felt today? (0 – a lot, 100 – none) (this question depended on the prior study interview; participants could opt out from this question)	Other
Have you experienced any significant obstacles to achieve your weight loss maintenance plan today? (0 – a lot, 100 – none)	Self-regulation
How much have you relied on your routines in your weight loss maintenance plan today? (0 – not at all, 100 – a lot)	Habit
How typical was your environment in relation to your weight loss maintenance plan today; e.g. access to food choices, physical activity opportunities? (100 – very different, 0 – as usual)	Environment
Personally relevant question(s) – optional, were incorporated in the daily assessment, based on self-reported obstacles and factors that may impact on WLM.	Other
Do you have any comments regarding your day today in relation with your weight maintenance plan? (open ended question)	N/A

Notes: Table shows how assessed variables fit into theoretical themes; however, the distinction is only indicative as some variables could be assigned to more than one theoretical theme; e.g. hunger was assigned under the theme of self-regulation and dealing with obstacle: 'feeling hungry' but it could also be classified under the theme of resources.

measures were based on theoretical predictions of behaviour maintenance (Kwasnicka et al., 2016) and were designed to capture day-to-day changes and intra-individual variability. Measures were piloted for four weeks with a sample of four volunteers. Similar measures were also piloted and used in two ongoing projects taking place at Newcastle University (McDonald, Hobbs, White, & Sniehotta, 2014, Newham, Presseau, Araujo-Soares, & Sniehotta, 2014).

Measuring physical activity and weight

To track physical activity and weight, participants were given a wireless activity monitor (THE ONE Fitbit™) and a wireless set of scales (Aria Scale Fitbit™). Participants were asked to wear the activity monitor daily, from when they woke up and left bed until they went back to bed in the evening. Participants were asked to weigh themselves once a day at a time pre-specified by them, preferably under similar circumstances (e.g. in the morning, before eating and dressed in underclothes).

Participants set up their on-line accounts for the devices and were free to monitor their progress and to access their own data at any time during the study on the Fitbit™ platform. The outcome measured with the activity monitor used for analysis was step count. Other activities (e.g. cycling), if self-reported in the Fitbit™ platform, were converted into step-equivalents and automatically added to the number of steps on the given day using algorithm included within Fitbit™ platform. The device was worn on a stable area of the trunk.

The outcome measured daily with the wireless scales used for analysis was weight; participants decided on a preferable weight unit: pounds, stones and pounds, or kilograms; all converted to kilograms for data analysis. Fitbit™ devices are reported as validated and reliable (Takacs et al., 2013) to receive objectively estimated real time outcome data.

Procedure

The research was approved by Newcastle University Ethics Committee (REC 00648_1). The study took place in Newcastle upon Tyne (UK) between August 2013 and March 2014. The aim was to recruit between 5 and 10 individuals for at least 3 months, in line with recommendations for the n-of-1 design (Duan, Kravitz, & Schmid, 2013), in which the number of observations and not the number of participants determines study power. Recruitment was carried out online via social media, using Facebook and Twitter, and through community advertisements using existing networks, mailing lists, and engagement groups.

Participants attended an introductory session with a researcher; their eligibility was assessed and the study explained in detail; all participants provided written informed consent. They were asked to explain how they typically maintained their weight loss and describe their WLM plan by clarifying how active they typically were and what they typically ate on the days when they fully adhered to their WLM plan. WLM plan adherence was a self-reported outcome. The content of the WLM plan was different for each participant and it compromised several WLM strategies (e.g. avoiding certain snacks, following a certain physical activity plan); different goals were included (e.g. counting calories and complying with a specific calorie limit, reaching 10,000 steps a day), and different areas of focus (avoiding alcohol, following specific diet of choice, exercising frequently, making sure that emotions do not impact on weight loss plans). Then, participants decided on the specific suitable timing for the EMA assessments. They were given a list of EMA questions (Table 1) and had an opportunity to familiarise themselves with the questions and to clarify any items. In addition, participants could add up to three questions about person specific variable(s) which they felt had an impact on their WLM.

Participants were given the equipment and were shown how to use it. Together with a researcher, participants formed action plans and coping plans to use the activity monitor and the scales daily. Action plans followed a standard format of specifying when, where, and how equipment would be used (Gollwitzer, 1999); coping plans were based on barrier identification and forming plans for overcoming these barriers (Kwasnicka, Presseau, White, & Sniehotta, 2013). The researchers were able to externally monitor equipment use and battery levels; and to remind participants to use the equipment if they forgot to use it or wear it, or if the battery levels were low, and that increased compliance with the study protocol. After initial study set up, participants engaged with the study for 6 months. Participants did not receive any financial reimbursement for their participation, but were offered reimbursement of travel expenses for study appointments if required.

Inclusion and exclusion criteria

Study inclusion criteria were: adults who had intentionally lost over 5% of body weight in the previous year (self-reported) and who had a BMI of over 30 kg/m^2 before weight loss.[1] Participation required access to a smartphone, touchpad, or computer with internet connection, and wireless internet access at home to connect the wireless scales. Participants without their own mobile phone were offered the loan of a study smartphone (one participant took on this option).

Study exclusion criteria were: being come pregnant or planning to become pregnant in the next 6 months; not willing to learn how to use a study phone; not willing to use the phone regularly for study purposes; not having internet on the mobile phone/touchpad/computer and not willing to accept a contract update; and having a pacemaker or other internal device preventing the use of wireless scales.

Data analysis

Each participant's data were treated as a separate data-set and first analysed separately. Missing data were imputed using bootstrapping methods with the Amelia II software (http://gking.harvard.edu/amelia) with the R package (Honaker & King, 2010). Data were imputed separately for each data-set and for each data series (using the same procedures for dealing with missing data applied by Hobbs et al., 2013; Quinn et al., 2013). For participants who showed a lower response rate towards the end of the series (i.e. five consecutive observations missing and more than 25% of missing data per data unit (defined as 20 consecutive days)) data series were shortened for analysis. For temporal long-term missingness of data (e.g. two weeks of data missing due to holiday), before and after data series were combined following visual inspection of data trends. Less than 300 steps per day was considered a missing value. SPSS version 21 was used for all further analyses (Hinton, McMurray, & Brownlow, 2014). Visual inspection was performed to assess variability of each data series. Descriptive statistics for each data series within each data-set were computed.

A 'pre-whitening' procedure was applied to adjust for autocorrelation, in order to maximise the independence of individual data points (Bayazit & Önöz, 2007). This procedure was performed on each data series with high autocorrelation (higher than 95% CI). Only autocorrelation at lag 1 and at lag 7 was controlled for, interpreted as day-to-day correlations (lag 1) and weekly cyclical patterns (lag 7). The pre-whitened data series were used for subsequent analyses.

The relationship between weight and plan adherence, and also relationship between physical activity and plan adherence was assessed, both between and within participants using time series analysis. Each participant's series of independent variables were correlated with plan adherence and with physical activity measure. The association between each independent variable and outcome variable was indicated by correlation coefficient function at time lag 0, a correlation on the same day. Only correlations that exceeded 95% CIs were considered predictive.

Sensitivity analysis was also performed for other time lags, looking into the valence of a correlation coefficient function at other time lags, indicating temporal relationships in which two observations occurred. For cross-correlations, sensitivity analysis lag -1 (day before) and lag 1 (day after) were employed. For instance, a positive lag suggests that the first variable precedes the second and a negative lag suggests that the second variable precedes the first.

Results

Participants and outcome variables

A total of 15 individuals met the study inclusion criteria and were invited to take part in the study. Two people did not take part due to wireless internet connection problems and one person discontinued participation after losing the activity monitor and deciding not to use the scales. Four people participated in the study for less than 3 months, and

Table 2. Summary of participants' characteristics and outcome variables.

P	Sex	Age in 2014	Weight at the start	Weight at 6th month	BMI at the start	BMI at 6th month	Adherence to the plan	Average step count
1	F	56	94.79	95.97	35.03	35.59	71.48_1 (26.37)	4473.23_1 (3699.53)
2	F	56	76.73	71.61	27.65	25.79	68.00_1 (31.21)	$10{,}617.00_1$ (3653.77)
3	F	50	86.23	81.41	35.34	34.32	66.01_1 (25.25)	10,611.26 (4422.30)
4	F	45	63.54	60.45	23.58	22.54	63.72_1 (13.98)	$11{,}552.58_1$ (3332.66)
5	M	50	129.75	124.53	42.7	41.67	89.20_1 (16.36)	8025.84 (3721.80)
6	M	61	86.11	77.79	25.49	24.77	86.89 (15.83)	$10{,}055.63_7$ (5153.19)
7	F	50	96.64	101.01	34.7	36.22	47.06_1 (24.80)	7477.56 (3401.87)
8	F	64	72.70	73.47	25.86	27.78	51.46_1 (13.04)	5960.10_1 (2703.83)

Notes: P – participant, F – female, M – male, BMI universally given in units of kg/m^2, weight in kilograms, and standard deviations in brackets; weight at the start and weight at 6th month was objectively measured using the Aria Fitbit™ scales. Numbers in subscript indicate lag of significant autocorrelations, and they are further described in autocorrelation sub-section.

their results were excluded from the analysis. The final sample included eight individuals whose characteristics are described in Table 2, together with a summary of outcome variables: weight recorded at the start of the study and at 6 months, BMI at these time points in units of kg/m^2, and descriptive statistics for average plan adherence and average step count. The average age was 54 (*SD* = 6.39, range 41–64) years.

Compliance with study protocol

Most participants showed high compliance with wearing the activity monitor (mean = 5.37 missing days, *SD* = 5.95 for 6 months; Table 3), varying from 0% (0 missing days) to 10.49% (19 missing days). The EMA compliance was variable (mean 15.09%, *SD* = 9.09%), with the number of missing values varying between participants (range 1.71–24.60%). Data series for three out of eight participants were shortened. Two participants had study breaks due to holiday travel (two weeks – participant 5 and three weeks – participant 1) and one participant's data series was shortened due to low EMA adherence in the last 4 weeks (participant 7).

Time series autocorrelations and descriptive statistics

Assessment of time series autocorrelations showed that out of 127 data series, 90 showed significant daily autocorrelations (at lag1) and 5 showed significant weekly cycles (at lag7), all of which were controlled for in further analysis (Table 4).

Table 4 shows means and standard deviations of assessed predictive variables and series controlled for autocorrelation. Intra-individual variability in WLM variables was observed in all eight participants; five participants included pain measures, two participants added an additional personal predictor of WLM, namely influence of weather (participant 3) and family (participant 4).

Table 3. Compliance with EMA procedures.

Participant number	Number of total missing values/Number of observation points (days; number of data series)	Percentage of total missing values	Number of days with less than 300 steps
1	436/2534 (181; 14)	17.20	19
2	612/3204 (178; 18)	24.15	4
3	220/3276 (182; 18)	6.71	0
4	53/3094 (182; 17)	1.71	2
5	669/2890 (170; 17)	23.14	2
6	845/3434 (202; 17)	24.60	7
7	422/2448 (153; 16)	17.23	6
8	186/3094 (182; 17)	6.01	3

Notes: Days with less than 300 steps were considered as missing values – usually days when participants forgot to wear activity monitor. Data series are adjusted for time series breaks. We could not estimate the compliance with Aria scale use, because we could not access an algorithm that Fitbit™ uses for missing weight values that are automatically imputed. We expect that compliance with Aria scales was similar to the compliance with Fitbit activity monitor.

Table 4. Predictive variables assessed (means and standard deviations) and time lags.

	Maintenance motives			Self-regulation					Habit	Personal resources				Environment		Other	
P	Motivation	Importance	Benefits	Awareness	Obstacles	Confidence	Hunger	Temptation	Routines	Stress	Sleep	Energy level	Happiness	Context	Social support	Pain	Additional*
P1	84.27_1	89.06_1	48.76_1	87.44_1	60.10	80.47_1	87.81_1	65.05	73.41_1	56.15_1	7.06	58.23_1	86.94_1	77.55_1	77.88_1		
	(23.21)	(21.28)	(28.45)	(22.23)	(29.11)	(25.45)	(26.58)	(28.46)	(29.68)	(27.88)	(.98)	(15.93)	(20.22)	(29.02)	(28.79)		
P2	87.62_1	94.02_1	81.06_1	88.93_1	72.88_1	87.31_1	65.56	65.33	43.33_7	70.84_1	5.08_1	66.75_1	75.11_1	79.24_1	57.99_1	47.91	
	(23.70)	(16.57)	(27.96)	(21.92)	(33.56)	(22.67)	(27.62)	(35.02)	(27.42)	(29.95)	(1.19)	(30.28)	(26.41)	(31.41)	(32.32)	(26.27)	
P3	87.33_1	96.10_1	85.33_1	92.20	63.06_1	81.83_1	64.17_1	38.02_1	61.40_1	52.52_1	6.76_7	73.09_1	52.55_1	65.54_1	49.56_1	14.88_1	4.59
	(12.67)	(9.03)	(14.67)	(11.59)	(31.19)	(13.49)	(20.81)	(28.64)	(31.54)	(28.29)	(.90)	(16.91)	(26.29)	(32.30)	(22.66)	(15.97)	(13.01)
P4	69.64	68.06_1	58.23_1	68.94_1	51.31	62.37	56.49_1	60.22_1	68.92_1	55.14	8.01	53.79	53.63	59.80_1	42.06		55.13_7
	(13.30)	(13.75)	(16.45)	(13.08)	(21.79)	(15.42)	(15.17)	(20.01)	(14.17)	(17.93)	(1.00)	(16.59)	(15.13)	(20.92)	(20.92)		(23.47)
P5	97.40_1	99.32_1	98.42_1	99.98_1	84.45_1	93.79_1	80.91	89.62_1	90.54	84.20	6.77	72.63_7	89.87_1	85.91_1	99.92_1	21.35_1	
	(8.00)	(3.68)	(9.70)	(.02)	(22.97)	(14.40)	(12.26)	(15.45)	(17.13)	(13.47)	(.97)	(13.80)	(10.80)	(23.08)	(.89)	(28.64)	
P6	97.33	97.78	98.21	99.05	90.74_1	96.38	86.89	86.38	93.69	93.10_1	6.86	86.11_1	95.23	93.03_1	97.29	30.72_1	
	(10.18)	(10.17)	(10.07)	(5.38)	(19.19)	(12.06)	(15.95)	(17.93)	(14.08)	(18.10)	(1.25)	(21.38)	(14.72)	(23.15)	(10.46)	(29.45)	
P7	58.37_1	50.49_1	44.61_1	47.83_1	37.88_1	58.63_1	59.55_1	33.93_1	45.70_1	55.37_1	8.13	48.12_1	66.36_1	48.72_1	45.14_1		
	(21.75)	(23.10)	(22.55)	(24.50)	(22.96)	(21.99)	(20.30)	(21.44)	(25.62)	(25.95)	(1.21)	(20.36)	(16.47)	(23.62)	(22.45)		
P8	67.81_1	72.12_1	60.98_1	56.17_1	47.63_1	62.22_1	51.32_1	49.90_1	55.95_1	57.41_1	6.73	54.29_1	63.75_1	57.31_7	33.47_1	24.14_1	
	(12.90)	(12.84)	(15.35)	(14.57)	(15.32)	(11.92)	(13.27)	(14.34)	(15.54)	(19.04)	(.99)	(18.13)	(16.89)	(15.80)	(13.87)	(24.56)	

Notes: Numbers in subscript indicate lag of significant autocorrelations, *n* vary for each participant. Standard deviations in brackets; P – participant number. *Additional: Two participants added a personal predictor of WLM, namely influence of weather (participant 3) and family (participant 4).

Predicting self-reported WLM plan adherence

Bivariate relationships between each theory-driven predictor and self-reported WLM plan adherence ranged from 15 to 17 per participant (15 if no pain measures and additional measure were added). In total, 127 separate relationships were examined, 102 of which reached significance (i.e. cross correlations that exceeded 95% CI; Table 5).

Maintenance motives

Motivation was associated with WLM plan adherence which was significant in all participants (range r_{lag0} = .19–.46). The correlation coefficients showed medium strength correlations[2] and one small. The higher the reported motivation to follow a personal WLM plan, the better the WLM plan adherence reported for that day (prospective motivation). Importance (range r_{lag0} = .25–.45) was less predictive and showed significant correlations in all participants apart from one, with four of small and three of medium strength. Appreciation of weight loss benefits (range r_{lag0} = .28–.54) showed significant correlations in all participants, with one small, six medium and one of high strength. The higher the importance of WLM, and the more the person appreciated the benefits of WLM, the higher the WLM plan adherence.

Self-regulation

Awareness of the WLM plan (range r_{lag0} = .32–.69) significantly predicted WLM plan adherence in all participants; correlations were medium in four participants and high in four. On the days when participants were more aware of their WLM plan, their WLM plan adherence was consistently rated higher. The number of obstacles and the number of temptations experienced were usually associated with WLM plan adherence, which was significant in all apart from one participant for both obstacles (range r_{lag0} = .29–.70), and temptations (range r_{lag0} = .19–.74). Most correlations for number of obstacles and WLM plan adherence were high. For temptation and plan adherence, correlations were small in one participant, medium in one, high in three, and very high in two participants. The higher the number of reported obstacles to adhere to the WLM plan or the higher the number of temptations participants faced, the less likely they were to follow the WLM plan.

Confidence to follow the WLM plan showed significant associations with WLM plan adherence in all participants (r_{lag0} = .26–.44), with one small and seven medium correlations. The higher the confidence to follow WLM plan reported, the better the WLM plan adherence reported for that day. Hunger had lower predictive utility (r_{lag0} = .31–.61) and significantly correlated with plan adherence in only five participants, showing medium correlations in four participants and high in one participant; the higher the hunger levels, the lower the WLM plan adherence.

Habit

Routines were a consistent predictor of WLM plan adherence (range r_{lag0} = .15–.80), significantly predicting WLM plan adherence in all participants. On the days when participants were more likely to follow their routines, their WLM plan adherence was

Table 5. Cross-correlations between adherence to the WLM plan and theoretical WLM variables.

Theme	Maintenance motives			Self-regulation					Habit	Personal resources				Environment		Other	
P	Motivation	Importance	Benefits	Awareness	Obstacles	Confidence	Hunger	Temptation	Routines	Stress	Sleep	Energy level	Happiness	Context	Social support	Pain	Additional*
P1 (.075)	.320**	.293**	.422**	.575**	.295**	.335**	.026	.194**	.775**	−.049	−.122	−.006	.140	.530**	.645**	na	na
P2 (.076)	.369**	.259**	.446**	.475**	.579**	.448**	.317**	.382**	.156*	.270**	.066	.433**	.450**	.327**	.183*	−.042	na
P3 (.076)	.375**	.267**	.284**	.329**	.709**	.342**	.327**	.559**	.720**	−.016	−.123	.342**	−.031	.605**	.452**	−.149	−.225**
P4 (.076)	.303**	.279**	.484**	.482**	−.033	.268**	.027	.049	.487**	−.066	.197*	.421**	.391**	.324**	.293**	na	−.216**
P5 (.080)	.194*	.094	.308**	.339**	.622**	.342**	.398**	.743**	.680**	.196*	−.031	.329**	.162*	.591**	.423**	.090	na
P6 (.071)	.307**	.355**	.545**	.601**	.571**	.354**	.611**	.726**	.724**	.455**	−.060	.502**	.392**	.414**	.519**	−.020	na
P7 (.081)	.321**	.336**	.500**	.695**	.585**	.430**	.066	.545**	.801**	.055	.074	.457**	.289**	.669**	.632**	na	na
P8 (.075)	.469**	.456**	.467**	.587**	.545**	.426**	.319**	.570**	.604**	.134	−.035	.390**	.153*	.546**	.191*	−.172*	na

Notes: NA – not applicable; standard error for lag0 in brackets; P – participant number. **Correlation is significant at the .01 level, * at the .05 level (two-tailed); non-significant correlation – did not reach 95% CI.

consistently rated higher. The correlations were found to be high in two and very high in four participants, but only medium in one and small in one participant.

Personal resources

Energy levels showed significant associations with WLM plan adherence in all participants apart from one (r_{lag0} = .32–.50). High energy levels were associated with high WLM plan adherence, with medium correlations in six participants and high in one. Happiness (r_{lag0} = .15–.45) was associated with plan adherence in six out of eight participants, with small and medium correlations. Pain showed the lowest predictive utility and was non-significant in four out of five participants who chose to include this variable. Stress and sleep were non-significant in four and seven participants, respectively, with mainly small correlation coefficients.

Environment

Environmental influences showed significant associations with WLM plan adherence in all participants (r_{lag0} = .32–.67). Familiarity of the environment was associated with high WLM plan adherence, with medium and large correlations. Social support (r_{lag0} = .18–.64) was significantly associated with plan adherence in all participants, with small correlations in three participants, medium in two, and high in three participants.

In two participants who self-selected additional variables that they believed were predictive of their WLM plan adherence, both selected variables showed significant correlations with outcome, namely weather ($r_{lag0} = -.22$) and impact of the family on participant's WLM plan adherence ($r_{lag0} = -.21$). These participants were less likely to follow their WLM plans when the weather was perceived to be bad (participant 3) or when the family had an impact on participant's WLM (participant 4), although both correlations were small.

The sensitivity analysis showed that lag0 was commonly the highest compared to correlations at other time lags (lag1 and lag-1). In rare cases when correlations at time lags other than zero were higher, often both time lags (e.g. lag0 and lag1) for the same comparison were non-significant. Most of the variables were correlated at time lag0 indicating predictive correlation on the same day; however, some showed a relationship at different time points (e.g. lag-1), suggesting that the explanatory variable preceded the outcome.

Predicting physical activity

The relationship between each predictor and physical activity was assessed (Table 6) and in total 127 correlations were examined, with 67 significant. Table 6 shows correlations for each of the predictors and step count measures; it also includes correlations between two outcomes (WLM plan adherence and step count). In six out of eight participants, WLM plan adherence was significantly correlated with the step count on that day (r_{lag0} = .18–.39), with small and medium correlations.

The strongest correlations for number of steps recorded daily were with self-reported energy levels, significant in seven out of eight participants (r_{lag0} = .31–.63).

Table 6. Correlations between step count and theoretical WLM variables.

Theme	Maintenance motives			Self-regulation					Habit	Resources				Environment		Other		
P	Motivation	Importance	Benefits	Awareness	Obstacles	Confidence	Hunger	Temptation	Routines	Stress	Sleep	Energy level	Happiness	Context	Social support	Pain	Additional	Following plan
P1 (.075)	.026	−.044	−.115	−.046	−.071	−.017	−.093	.036	.165*	−.131	.062	.134	−.022	−.155*	−.144	na	na	.180*
P2 (.076)	.232**	.195*	.193*	.195*	.332**	.221**	.151	.266**	−.013	.162*	−.135	.523**	.220**	.318**	.123	.054	na	.338**
P3 (.076)	.175*	.088	.005	.122	.289**	.148*	−.033	.200**	.445**	−.037	−.164*	.370**	−.035	.261**	.122	.015	−.210**	.316**
P4 (.076)	.227**	.186*	.408**	.331**	−.163*	.183*	.147	.104	.363**	−.221*	.139	.631**	.320**	.251**	.383**	na	−.045	.395**
P5 (.080)	−.080	−.045	.012	−.055	.153*	−.159*	.126	.145	.160*	−.001	−.034	.317**	.175*	.184**	.040	.169*	na	.146
P6 (.071)	.142	.154*	.254**	.166*	.195**	.210**	.185**	.270**	.284**	.152*	.055	.592**	.152*	.190**	.241**	−.001	na	.294**
P7 (.081)	−.020	−.076	.146	.050	.092	−.046	−.132	.135	.032	−.136	−.342**	.456**	.052	.092	−.022	na	na	.134
P 8 (.075)	.241**	.228**	.190**	.308**	.320**	.235**	.160*	.287**	.362**	.073	.028	.318**	.118	−.125	.008	−.168*	na	.255**

Notes: NA – not applicable; standard error for lag0 in brackets; P – participant number. **Correlation is significant at the .01 level, * at the .05 level (two-tailed); non-significant correlation – did not reach 95% CI.

The higher the energy level on the given day, the higher the physical activity level, with medium correlations in four participants and high in three. Other important predictors of activity were confidence to follow WLM plan (r_{lag0} = .14–.23), number of obstacles (r_{lag0} = .15–.33), ability to rely on the routines (r_{lag0} = .16-.44), and familiarity of the environment (r_{lag0} = .15–.31), with all four predicting variables significant in six out of eight participants, although with mainly medium or small correlations. The higher the confidence to adhere to the WLM plan, reported in the morning, the higher number of steps that day. The higher the number of obstacles to follow the WLM plan, the lower the step count. The higher the possibility to rely on the routines, and the more stable the environment, the higher the step-count.

Social support, sleep, and hunger were least likely to be associated with the step count. Correlations for each of the three aforementioned variables were non-significant in six out of eight participants. One self-selected personal variable showed a significant correlation with step count, namely influence of weather on the WLM plan adherence, but with only a small correlation coefficient (participant 3: $r_{\text{lag0}} = -.21$). There was a high variation in the number of explanatory variables which correlated with step-count (CI 95%), ranging from only 2 variables in 2 participants (participants 1 and 7) up to 13 variables in another (participant 6). Different variables were predictive for different participants in terms of strength of the correlation with step count. Step count data showed a less clear pattern of results and much lower correlations with predictive variables than WLM plan adherence.

Objective measures of weight

The weight and plan adherence for each participant across the study period is displayed in time plots (Appendix 1 in Supplemental data) showing how self-reported plan adherence corresponded with weight changes; slow and gradual weight changes were usually associated with changes in plan adherence. For instance, periods of low adherence to the plan were followed by weight gains. Out of eight individuals, two had slow and gradual weight increase (participants 1 and 8), three had gradual weight decrease (participants 2, 3 and 6), one had stable weight with small fluctuations (participant 4), and two showed weight decrease at the beginning of the study and then gradual increase in the following months (participants 5 and 7). For participants who gained weight during the study, an overall weight loss of at least 5% was still maintained.

Discussion

Summary of principal findings and relationship to prior knowledge

The psychological variables predicting WLM behaviours within individuals who have recently lost weight differed between individuals. Patterns of theoretical variables of behaviour maintenance contributing to the prediction and amount of variability accounted for, differed between participants for WLM plan adherence and physical activity. Different variables from each of the theoretical themes (Kwasnicka et al., 2016) were found to explain variability in outcomes in different individuals. Explanations for variables underpinning WLM demonstrated in this study *within* individuals were often in line with theory and with previous studies showing *between*-person comparisons. The results are discussed for each theoretical theme: maintenance motives, self-regulation, resources, habit, and environment.

Maintenance motives

For all participants, sustained motivation and appreciation of WLM benefits correlated with WLM plan adherence, which is in line with theory and with previous between-person WLM studies that highlight the prominence of maintenance motives (Elfhag & Rossner, 2005) and satisfaction with behavioural outcomes (Rothman, 2000) in order to maintain weight loss. Previous studies suggest that identity change is usually linked to a singular event and does not show day-to-day variation (Epiphaniou & Ogden, 2010); thus, motivation related to identity values was not assessed in this study.

Self-regulation

In all participants, awareness of a WLM plan significantly correlated with plan adherence. In line with several theories, active self-regulation including awareness of one's plan and goals is crucial for behaviour maintenance. Empirical between-person studies have shown that people who actively self-regulate are more likely to maintain their weight loss (Elfhag & Rossner, 2005; Ohsiek & Williams, 2011) which is in line with the within-person outcomes reported here. Participants reported daily on the obstacles and temptations experienced and on how hungry they were. Obstacles and temptations showed high negative correlations with WLM plan adherence. Results were in line with evidence suggesting that successful self-regulation is associated with the ability to overcome behavioural difficulties (Marlatt & George, 1984; Sniehotta, Schwarzer, Scholz, & Schüz, 2005). Hunger did not show significant correlations with WLM plan adherence in most participants. This finding was in contrast with previous studies that report hunger as an important predictor for WLM (Pasman, Saris, & Westerterp-Plantenga, 1999). Estimating and reporting hunger daily can be difficult as levels of hunger vary throughout the day; thus, future studies should assess hunger more often throughout the day to draw meaningful conclusions about the association.

Habits

Relying on established routines correlated strongly with WLM plan adherence in all participants, with high correlations for most participants. For some participants, routine was also related to daily step count. Numerous studies have shown that creating healthy eating and physical activity habits led to successful WLM (Lally, Chipperfield, & Wardle, 2007; Pronk & Wing, 1994). The findings presented provide the first evidence of the predictive utility of habit within participants in a WLM context. However, the predictive validity might also relate to the fact that only a single item measure was used to capture variability within this theme; therefore, future studies should include additional items and multiple measures of the construct (Gardner, Abraham, Lally, & de Bruijn, 2012).

Personal resources

Personal resource-based predictors showed limited predictive utility. No strong support was found for correlations between daily fluctuations of stress, pain, and sleep with study outcomes in most participants, in contrast with previous studies such as between-person comparisons for stress (DePue, Clark, Ruggiero, Medeiros, & Pera, 1995), pain (Larsson, 2003) and sleep (Beccuti & Pannain, 2011), associated with WLM and weight regain. Empirical studies (Klem, Wing, McGuire, Seagle, & Hill, 1997) suggest that having plentiful cognitive resources enhances WLM. Our findings suggest that there are within-person differences in the predictive utility of all three variables, and further within- and between-person comparisons are needed to more clearly define the relationships. The absence of strong relationships could also be due to the difference in temporal dynamics in the predictor; for example, if predictive variables vary over the day, the measurement is not likely to reflect outcomes aggregated over the day and n-of-1 methods are only as sensitive as they reflect the temporal dynamic of variables investigated.

Two other variables within the personal resource theme were found to be predictive for some participants. Fluctuations in energy levels and happiness were often correlated with following the WLM plan. Energy level was correlated with step count in all apart from two participants. Happiness was strongly correlated with both outcomes for some of the participants, in line with empirical studies that also show mixed results (Haedt-Matt & Keel, 2011). For instance, a meta-analytic review of EMA studies of affect and binge eating showed that positive as well as negative affect can trigger overeating (Haedt-Matt & Keel, 2011). Thus, effects were person specific, and being happy related to both success in following WLM plan in some participants and failure to follow it in others.

Environment

Participants were asked daily how typical their environment was in relation to their WLM plan, and familiarity of the environment was always correlated with WLM plan adherence. Similarly, a supportive and stable environment was theorised as a pre-condition for behaviour maintenance (Greaves, Reddy, & Sheppard, 2012). Several studies have shown that people are more likely to maintain their weight loss if their environment is WLM supportive and stable (Brown, Kelly, & Summerbell, 2007; Hill, Thompson, & Wyatt, 2005; Peters, Wyatt, Donahoo, & Hill, 2002), findings corroborated by the results reported here.

Social support was conceptualised as a part of the environmental context that impacts on behaviour maintenance (Deci & Ryan, 2010). Previous studies have shown that successful WLM was often underpinned by social support (Elfhag & Rossner, 2005). N-of-1 studies reported here showed a significant correlation in each participant with variable strength of correlations. A possible explanation for these finding may be in the question wording. Variation in responses may relate not to the variability of the support received, but to the perceived need for social support. As demonstrated in other studies, there are various ways in which others can support a person's WLM, some of which may be more effective than others (e.g. encouragement compared to personally giving health warnings (Stephens, Rook, Franks, Khan, & Iida, 2010)). Social support could be further investigated as a within-person factor in terms of need for social support and amount of support received. For both measures assessed within this theme, only single-item measures were used; therefore, additional items could improve the design in the future research.

Study strengths

This study used a novel combination of methods and technologies, underpinned by explicit theoretical themes derived from a systematic review of theoretical constructs used to explain behaviour change maintenance in within-person studies. Multiple predictors of outcomes were assessed to examine the applicability of the theory at an individual level.

Each of the theoretical predictors was derived from a theory review that systematically analysed explanations of behaviour maintenance (Kwasnicka et al., 2016). Some of the theories and explanations have been previously tested between people but, to our knowledge, none of them have been studies in within-person comparisons.

Variables predicting differences *between* individuals are often different from variables that predict differences *within* individuals measured at different time points (Craig et al., 2008; Johnston & Johnston, 2013). The n-of-1 design allowed us to examine maintenance-related themes within people for the predictions previously tested between people. The study results showed that WLM behaviours and their theoretical determinants vary considerably over time within individuals.

Novel technologies were used to collect data in real time. Applying cost-effective technology in the form of a pre-scheduled text messaging system and participants' own device of choice (Smartphone, tablet, computer) allowed efficient data collection. Participants' answers to daily questionnaires were time-stamped allowing us to assess the exact timing of survey completion; participants were not able to go back and fill in previous surveys.

Study limitations

Study limitations included a number of practical and technical challenges. This study was designed to be purely observational, but it included several BCTs (e.g. self-monitoring, using prompts and reminders); thus, participants' behaviour could be potentially altered by daily assessment. Although a recent systematic review of the question-behaviour effect has shown that the effect of asking participants' questions on changing their behaviour is not conclusive (Rodrigues, O'Brien, French, Glidewell, & Sniehotta, 2014), engaging in several study activities could potentially impact on study outcomes. Furthermore, we did not assess participants' dietary intake or eating behaviours, hence were unable to estimate energy intake. Excess energy intake is the primary driver of obesity; therefore, this should be assessed alongside energy expenditure in future studies. Moreover, we measured perceptions of, but not objective features of the environment. Digital technologies allow for the assessment of objective environments through geo-sensors and such assessments are desirable in future research.

Study implications

This study showed that the n-of-1 design is valuable to test if predictions demonstrated between people hold within individuals. It has been shown that not only one-off tests of predictions, but also assessment of changes and variations in cognitions, helps test hypotheses about health-related behaviour. Using the n-of-1 method is resource-intensive and requires repetitive assessment. This study demonstrated that using wearable devices and providing participants with multiple convenient ways to answer study questions ensured high response rate and compliance with the study protocol.

One challenge faced by behavioural interventionists is that lifestyle change and maintenance is underpinned by many variables. These variables include cognitions that continuously change the degree with which they impact on behaviour. Repeated assessment of the variables underpinning behaviour change maintenance allowed assessment of the relationship between the predictors and outcomes, uncovering the strongest correlations. Each behavioural option has a behaviour potential indicating the relative dominance of each response in the given context (Heckhausen & Beckmann, 1990; Rotter, 1960). Identifying which factors show the strongest correlations with assessed outcomes may allow the design of interventions that relate to the most predictive outcomes, applied at the time when behaviour change potential is highest. Variables underlying maintained weight loss are inter-related and often multiple variables play a role. This study showed that variables influencing WLM outcomes vary within people and that they change with time. Tailored and person-centred approaches may therefore enable the design of effective interventions to help people maintain a healthy weight. Delivering such interventions efficiently at scale will be a challenge.

Unanswered questions and future research

Future research should test explanations and predictors of WLM, and also intervene on the predictors which are shown to be significant. Gathering n-of-1 data allows interventionists to concentrate on specific predictors which are shown to have the most powerful influence on self-reported outcomes, activity, and weight changes. Future studies may examine this topic over an extended time period (e.g. one year) and may base tailoring of interventions on the cognitions that show the strongest associations with outcome variables.

In the future, combining wearable technology, social media, and other platforms will allow for real-time intervention that is modelled and tailored according to behaviour predictions (e.g. providing social support via social media when low on confidence, or enhancing awareness when routine changes if a person's WLM plan adherence is reactive to unstable contexts) (Gilmore, Duhé, Frost, & Redman, 2014). Research will need to determine whether such interventions can feasibly and cost-effectively be delivered at scale.

Time series analysis produces vast amounts of data and there is no established consensus on how to best analyse n-of-1 studies (Shamseer et al., 2015). Researchers reporting n-of-1 outcomes often treat each of the participants as a separate study. Presenting each participant as an independent study would allow assessment in more detail of changes and trends in each of the predictors and their relationship with each of the outcomes (Pindyck & Rubinfeld, 1998).

Conclusions

Our findings suggest that different predictors are important for WLM in different individuals and the variability of predictors and their impact on behaviour needs to be considered. The findings highlight the usefulness of the n-of-1 design to test theories explaining individual behaviour. Previous studies have presented outcomes aggregated across participants to explain differences in WLM between people. To design effective interventions it is crucial to understand not only between, but also within person differences. Cognitions underpinning successful WLM are likely to vary over time; thus, a better understanding of when people are more likely to successfully maintain their weight is needed.

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Supplemental data

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Notes

1. In this study WLM was defined as intentional weight loss of at least 5% of body weight, meaning weight loss reported as clinically significant; i.e. sufficient to lead to health benefits, with no time restrictions (Franz et al., 2007).
2. The description follows the standard classification: correlation coefficients between 0 and .1 are considered very small, correlation coefficients between .10 and .30 are considered small, from .30 to .50 medium, from .50 to .70 high, between .70 and .90 very high, and above .90 nearly complete (Hopkins, 1997; Kotrlik & Williams, 2003).

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