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Testing motivational and self-regulatory mechanisms of action on device-measured physical activity in the context of a weight loss maintenance digital intervention: A secondary analysis of the NoHoW trial

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ABSTRACT

Background: To date, few digital behavior change interventions for weight loss maintenance focusing on long-term physical activity promotion have used a sound intervention design grounded on a logic model underpinned by behavior change theories. The current study is a secondary analysis of the weight loss maintenance NoHoW trial and investigated putative mediators of device-measured long-term physical activity levels (six to 12 months) in the context of a digital intervention.

Methods: A subsample of 766 participants (Age = 46.2 ± 11.4 years; 69.1% female; original NoHoW sample: 1627 participants) completed all questionnaires on motivational and self-regulatory variables and had all device-measured physical activity data available for zero, six and 12 months. We examined the direct and indirect effects of Virtual Care Climate on post intervention changes in moderate-to-vigorous physical activity and number of steps (six to 12 months) through changes in the theory-driven motivational and self-regulatory mechanisms of action during the intervention period (zero to six months), as conceptualized in the logic model.

Results: Model 1 tested the mediation processes on Steps and presented a poor fit to the data. *Model 2* tested mediation processes on moderate-to-vigorous physical activity and presented poor fit to the data. Simplified models were also tested considering the autonomous motivation and the controlled motivation variables independently. These changes yielded good results and both models presented very good fit to the data for both outcome variables. Percentage of explained variance was negligible for all models. No direct or indirect effects were found from Virtual Care Climate to long term change in outcomes. Indirect effects occurred only between the sequential paths of the theory-driven mediators.

Conclusion: This was one of the first attempts to test a serial mediation model considering psychological mechanisms of change and device-measured physical activity in a 12-month longitudinal trial. The model explained a small proportion of variance in post intervention changes in physical activity. We found different pathways of influence on theory-driven motivational and self-regulatory mechanisms but limited evidence that

Abbreviations: PA, Physical Activity; MVPA, Moderat-to-Vigorous Physical Activity; SDT, Self-Determination Theory; SRT, Self-Regulation Theory.

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these constructs impacted on actual behavior change. New approaches to test these relationships are needed. Challenges and several alternatives are discussed.
Trial registration: ISRCTN Registry, ISRCTN88405328. Registered December 16, 2016, https://www.isrctn.com/ISRCTN88405328.

Long term weight loss maintenance is difficult and is complex both from a physiological and a psychological perspective (MacLean et al., 2015; Wing & Phelan, 2005). Sustained health behaviors over time such as increased levels of physical activity (PA) contribute to weight loss maintenance (Butryn et al., 2021; Lee, Djoussé, Sesso, Wang, & Buring, 2010; X. Wang et al., 2008; Wing et al., 2008) and are key to halting the increasing rates of obesity-related diseases (Saint-Maurice et al., 2019; Wadden, Tronieri, & Butryn, 2020). PA has protective effects as it decreases the risk of weight relapse by 1% for every additional 10 min of total regular PA (Crochiere et al., 2020).

Problems associated with traditional behavioral interventions relate to high delivery costs of individualized face-to-face interventions due to logistical difficulties (e.g., time and personnel resources). This represents a crucial barrier to performing large-scale and long-term health interventions (Arigo et al., 2019). Digital technologies can help tackle physical (in)activity and promote long term weight management, with high scalability and potential cost-effectiveness (Arigo et al., 2019; Yardley, Choudhury, Patrick, & Michie, 2016).

However, the literature presents mixed results. Some digital behavior change interventions report better weight outcomes (Leahey et al., 2016; Thomas, Vydelingum, & Lawrence, 2011) when comparing control and intervention groups, but others report marginal or no significant results for weight outcomes (Brindal, Hendrie, Freyne, & Noakes, 2019; Collins et al., 2012; Gerber et al., 2013; Nakata, Sasai, Tsujimoto, Hashimoto, & Kobayashi, 2019; Sniehotta et al., 2019; Wing et al., 2008). This is also true for PA outcomes as some studies report no significant results when comparing the digital condition versus control (Brindal et al., 2019; Collins et al., 2012; Gerber et al., 2013; Nakata et al., 2019), others report better PA outcomes (Sniehotta et al., 2019) while some even report worse PA outcomes (Coughlin et al., 2013; Wing et al., 2008). These mixed results may depend on the fact that few digital behavior change interventions for weight loss maintenance focusing on PA promotion used a sound intervention design underpinned by behavior change theories and predefined logic models (Encantado, et al., 2022).

Theories of behavior change hypothesize underlying mechanisms of action (Hagger, Moyers, McAnally, & McKinley, 2020; Hekler et al., 2016) and interrelated behavior change techniques that should be used in the design of effective digital behavior change interventions (Connell et al., 2019; Teixeira & Marques, 2017). This theoretical clarification of why, how, and when interventions achieve their effects, provide benefits for intervention development and evaluation-because they can be empirically tested (Hekler et al., 2016; Suls et al., 2020). Therefore, there is a need to design and implement behavioral interventions that are grounded on theory-based logic models that test the mechanisms of action involved in long-term behavioral change (Hagger et al., 2020; Michie et al., 2018). However, studies have only recently begun to implement these approaches, and few studies have tested the indirect effect of the intervention on behavior through psychological mechanisms using mediation techniques (Hagger et al., 2020). Those who did, often focused on single mediator analysis in an exploratory fashion, and often did not report the proportion of PA outcome variance explained by the model. For instance, a recent series of meta-reviews suggested little evidence for behavioral intervention mechanisms of action, that is, only few reviews found studies that directly or indirectly tested the mediation processes that represent the mechanism of action (Hennessy, Johnson, Acabchuk, McCloskey, & Stewart-James, 2020; Suls et al., 2020; T. E. Wilson et al., 2020).

The NoHoW project was one of the first attempts to provide a proof-of-concept theory-based digital behavior change intervention with a 2 × 2 factorial design 18-month randomized controlled trial to promote weight loss maintenance through the regulation of PA and eating behavior (Scott et al., 2019). The current study investigated the theory-based mechanisms of action that promote long-term PA outcomes using data from the NoHoW trial. We used a mediation analysis to test the logic model at 12-month follow-up based on Self-Determination Theory (SDT) and Self-Regulation Theory (SRT). Both theories presented promising results regarding weight management both supporting long-term success and promoting well-being (Ng, Ntoumanis, Thøgersen-Ntoumani, Stott, & Hindle, 2013; 2014; Silva et al., 2010; Hennessy et al., 2020).

The NoHoW logic model theorized as follows (for a detailed description see: Marques et al., 2021; Scott et al., 2017): i) the perceived autonomy supportive environment of the digital intervention would have a beneficial impact on participants' basic psychological needs satisfaction and would also foster intrinsic goal contents (Ntoumanis et al., 2020; Sheeran et al., 2020); ii) nurtured basic psychological needs would promote increases in autonomous motivation and decreases in controlled motivation (Deci & Ryan, 2000; Ryan & Deci, 2017); iii) increased autonomous motivation would reinforce the self-regulatory skills that will support and maintain volition to be physically active (Hagger & Chatzisarantis, 2014; Lakerveld et al., 2020; Wing, Tate, Gorin, Raynor, & Fava, 2006).

The aim of the present study was to conduct a mediation analysis investigating i) whether changes in the theory-driven mediators included in the intervention content during the first six months (active intervention period) accounted for changes in device-measured PA outcomes in the subsequent six-month period (six to 12 months); and ii) the inter-relationships between the theory-driven hypothesized mediators.

1. Methods

1.1. Sample

A total of 1627 participants were eligible to participate in the study (Mean Age = 44.0 ± 11.9 years; 68.7% female) across three countries: Denmark (n = 536); Portugal (n = 536); United Kingdom (n = 555). A subsample of 766 participants (Denmark n = 265; Portugal n = 274; United Kingdom n = 227; Mean Age = 46.2 ± 11.4 years) completed all questionnaires via the electronic platform Qualtrics™ and had all device-measured PA data available at baseline as well as for the sixth and the 12th month. To the present analysis our aim was to test the logic model despite group allocation, therefore the data from the four arms of the intervention were pooled into one group.

The NoHoW Trial was funded by the European Union's Horizon 2020 Research and Innovation Programme (grant agreement number 643309). A detailed description of the NoHoW trial procedures can be found elsewhere (Marques et al., 2021; Scott et al., 2019). The trial was registered with the ISRCTN registry (ISRCTN88405328). Ethical approval was granted by all local institutional ethics committees at the Universities of Lisbon (17/2016; 20-Feb-2017), Leeds (17–0082; 27-Feb-2017), and the Capital Region of Denmark (H-16030495; 8-Mar-2017). Participants were assigned to one of four intervention conditions that have access to different theory-based digitally delivered content:

Arm 1. Active Control: access to the self-monitoring tools.

Arm 2. Motivation and Self-regulation: access to the self-monitoring tools and to motivational and behaviour regulation strategies.
Arm 3. Emotional Regulation: access to the self-monitoring tools and to emotion regulation strategies.
Arm 4. Combined Condition: access to the self-monitoring tools, to motivational and behaviour regulation strategies, and to emotion regulation strategies (i.e., combination of Arms 2 and 3).

The NoHoW digital intervention content was delivered in seventeen psycho-educational sessions distributed in eight themes across intervention arms (conditions 2, 3 and 4), using various modes of delivery such as interactive quizzes, educational videos, successful testimonies, and interactive graphics. The digital intervention development procedures have been described elsewhere (Marques et al., 2021).

The current mediation analysis was based on the theoretical underpinnings of Self-Determination Theory (Deci & Ryan, 2000; Ryan & Deci, 2017) and Self-Regulation Theories (Carver & Scheier, 1982; Kanfer & Gaelick-Buys, 1991; Wing et al., 2006), two core theoretical approaches to understanding long term weight management and sustained PA (Teixeira, Carraça, et al., 2015; Teixeira, Marques, et al., 2015). These approaches are sometimes referred as complementary for the behavior change process assuming that motivation energizes and directs the new behavior and adequate self-regulatory skills provide the behavioral tools to act upon the goal and/or motive (Hagger & Chatzisarantis, 2014; Lakerveld et al., 2020; Sniehotta, 2009).

1.2. Outcome variables

Physical activity was assessed using a validated commercial fitness tracker device: The Fitbit Charge 2™ (San Francisco, CA, USA) (FC2) (Mikkelsen et al., 2020; Reddy et al., 2018), which estimated daily steps and minutes of light, moderate and vigorous PA for 12 months. A composite of moderate-to-vigorous PA (MVPA) was computed. Full description of data handling algorithm is described elsewhere (O'Driscoll et al., 2020). Briefly, procedures were taken to identify non-wear time through the evaluation of the valid heart rate measurements and non-missing data were scaled to daily totals through the application of the 'NoHoW algorithm', described previously (O'Driscoll et al., 2020). In the present analysis, the average daily steps were calculated for each measurement period (baseline to six months; six to 12 months) and the same procedures were used for the aggregated variable of moderate-to-vigorous intensity PA time (minutes/day).

1.3. Mediators

1.3.1. Motivational variables

Treatment autonomy support was assessed via the Virtual Care Climate Questionnaire (Smit, Dima, Immerzeel, van den Putte, & Williams, 2017) which measured perceived autonomy-support in a virtual care setting (i.e., digital intervention; e.g., "NoHoW digital intervention answers my questions fully and carefully"). The scale included twenty items and a score range of seven points (1-strongly disagree; 7-strongly agree). Higher mean scores represented higher levels of perceived support for autonomy from the NoHoW digital intervention. Virtual Care Climate Questionnaire demonstrated good reliability (McDonald's $\omega = 0.95$).

Basic Psychological Needs Satisfaction was assessed using the Basic Psychological Needs Satisfaction Scale (Ng et al., 2013; Richer & Vallerand, 1998). It comprised twelve items distributed in three subscales, one for each basic psychological need (Autonomy; Competence; Relatedness; e.g., "I feel I make efforts to maintain weight willingly"). Scoring ranged from one to seven points scale (1-strongly disagree; 7-strongly agree); a global composite was calculated, and higher mean scores represented higher basic psychological needs satisfaction. The Basic Psychological Needs Satisfaction Scale demonstrated good reliability (Individual factors McDonald's $\omega > 0.77$; global basic psychological needs composite McDonalds's $\omega = 0.92$).

Goal Content was assessed by the Goal Content for Weight Management Scale (Encantado, Marques, et al., 2021), comprising thirteen items grouped in four subscales (Health Management; Challenge; Social Recognition; Image; e.g., "I manage my weight to improve my appearance"), and scale scoring ranged from one to seven points (1-strongly disagree; 7-strongly agree). Two theoretical dimensions were computed based on the SDT framework to discriminate between intrinsic goals (Health Management; Challenge) and extrinsic goals (Social Recognition; Image). Higher mean scores represented a higher expression of each goal content for weight management (extrinsic and intrinsic). The Goal Content for Weight Management Scale demonstrated good reliability (Individual factors McDonald's $\omega > 0.78$; Intrinsic goal factor: McDonalds's $\omega = 0.81$; Extrinsic goal factor: McDonalds's $\omega = 0.82$).

Behavioral Regulations were assessed by the Behavioral Regulations for Exercise Questionnaire-3 (BREQ) (Markland & Tobin, 2004; P. M. Wilson, Todd Rogers, Rodgers, & Cameron Wild, 2006). The scale comprised 24 items distributed into six subscales: Intrinsic, Integrated, Identified, Introjected, External, and Amotivation. Scale scoring ranged from one to seven points (1-not true for me; 7-very true for me) and higher scores represented higher manifestation of a self-determined behavioral regulation. Two theoretical dimensions were computed based on the SDT framework to discriminate between good quality motivation (Autonomous Motivation that includes intrinsic, integrated, and identified regulations) and low-quality motivation (Controlled Motivation that includes introjected and external regulations). The BREQ-3 demonstrated good reliability on each behavior regulation composite (Individual factors McDonald's $\omega > 0.80$; Autonomous motivation McDonalds's $\omega = 0.95$; Controlled Motivation: McDonalds's $\omega = 0.77$).

1.3.2. Self-regulation variables

Action Control was assessed by the Action Control Scale (Sniehotta, Scholz, & Schwarzer, 2005). The Action Control Scale comprised eight items grouped that addressed the different action control facets: self-monitoring, awareness of standards, and self-regulatory effort (e.g., "During the last four weeks I have consistently monitored my physical activity"). Scoring ranged from one to five points scale (1-strongly disagree; 5-strongly agree) and higher mean scores represented higher action control. The Action Control Scale demonstrated good reliability (McDonalds's $\omega = 0.90$).

Action Planning and Coping Planning: Self-regulatory capacities for weight management were assessed by the Action Planning (Sniehotta, Scholz, et al., 2005; Sniehotta, Schwarzer, Scholz, & Schüz, 2005) that comprised four items and by the Coping Planning scale, which comprised 14 items (e.g., "I have a specific plan regarding how much activity to do to maintain my current body weight"). Scoring ranged from one to five points scale (1-strongly disagree; 5-strongly agree) and higher scores represented increased self-regulatory skills for weight management. The Action Planning and the Coping Planning Scales for Weight Management demonstrated good reliability (McDonalds's $\omega =$ 0.82 and 0.95, respectively).

1.4. Procedures

Participants completed the battery of psychometric instruments online before each clinical investigation day at baseline, six, and 12 months. Treatment support was retrospectively assessed via Virtual Care Climate questionnaire following the intervention completion, reporting to the perceived treatment autonomy support from the digital platform during the first six months. The NoHoW Logic Model for PA (Arm 2) is depicted in Figure 1.

1.5. Statistical analysis

The NoHoW Trial data set was thoroughly analyzed by the

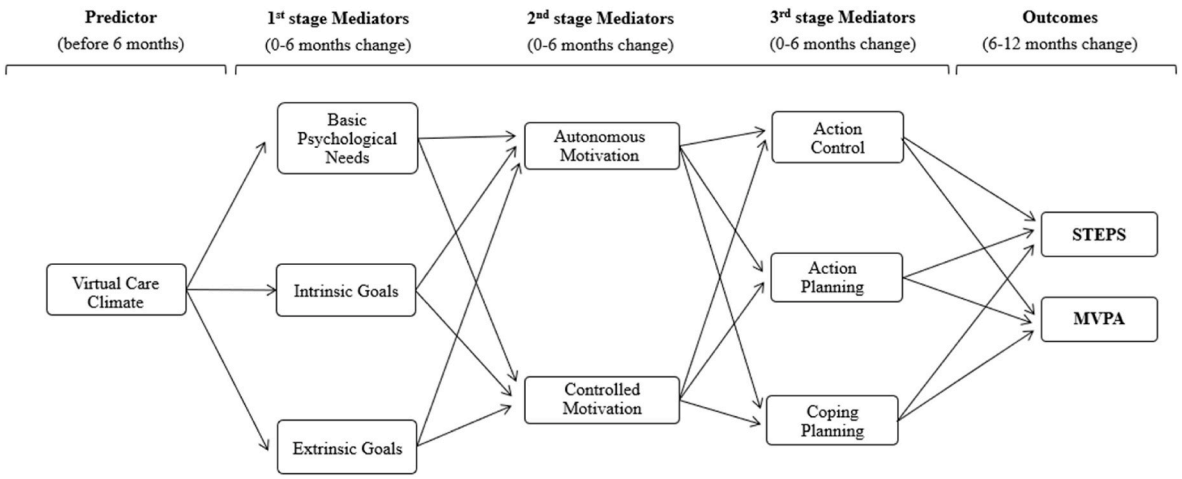

Figure 1. NoHoW trial Arm 2 logic model for long-term physical activity outcomes
Notes. MVPA: Moderate-to-Vigorous Physical Activity.

consortium experts. Although with so many variables recorded, there was multicollinearity in the full set of data, this was not a problem with the subset of variables which we used in our modelling. There were no data which we considered outlying enough to cause concern.

Changes in mediators during the first six months were captured by residuals (from hereon mentioned as RΔ) computed from the six-month scores regressed to the baseline scores. The same procedure was used regarding outcome variables but using 12-month scores regressed to six-month scores to capture the subsequent changes occurred during the six months of intervention. This procedure was previously followed by others (Palmeira et al., 2009, 2010) and is recommended by Cohen and colleagues (Cohen, Cohen, West, & Aiken, 2013), which computes a score that is orthogonal to the independent variable and is a better measure to capture change than the simple pre-post subtraction.

Structural equation modelling techniques were used to test the hypothesized logic model with MPLUS 7 software (Muthén & Muthén, 2016). Two models were tested using the robust maximum likelihood (MLR) estimator differentiated by the type of PA outcome: *model 1* tested the fit of the logic model regarding post-intervention change of Steps; *model 2* tested the fit of the logic model regarding post-intervention change in MVPA time. Both models were tested the configural invariance of the models across countries. To assess model fit we used the following recommended fit indices (Hu & Bentler, 1998; Kline, 2015): comparative fit index (CFI >0.90); Tucker Lewis index (TLI >0.95); the root mean square error of approximation (RMSEA <0.80); the standardized root mean square residual (SRMR <0.80); and the chi-square test (chi-square/degrees of freedom <3.0). We used the R^2 as a measure of the proportion of explained variance in outcome variable accounted by the mediators and the predictor variable (MacKinnon & Tofighi, 2012).

Secondly, to thoroughly inspect the path model and test the indirect effects, bootstrapping technique confidence intervals with a 5000-resampling was employed (significance of $p < .05$ and the 95% confidence interval not including 0) (Hayes, 2017; Preacher & Hayes, 2008, 2014). Also, bootstrapping technique does not require the assumption of normality and it is considered more robust than the normal theory approach (Hayes, 2017).

2. Results

Sample characteristics are presented in Table 1. The correlation matrix between psychosocial and PA variables is available in Additional File 1. Two different models were tested. M*odel 1* tested the mediation model on device-measured Steps and presented a poor fit to the data: *Model* 1 MLR $\chi2 = 117.293$, df = 20 (5.86), $p = .001$; CFI = 0.881; TLI = 0.733; RMSEA = 0.080 (90% CI = 0.066, 0.094); SRMR = 0.071. The second model included device measured MVPA and also presented a poor fit to the data: *Model 2*: $\chi2 = 124.541$, df = 20 (6.23), $p = .001$; CFI = 0.873; TLI = 0.715; RMSEA = 0.083 (90% CI = 0.069, 0.097); SRMR = 0.072. The percentage of the outcome variables variance explained by each model was small and non-significant (Steps $R^2 = 0.010$, $p = .18$; MVPA $R^2 = 0.008$, $p = .13$).

Table 1
Participants' characteristics for the included subsample.

Characteristics	All (N = 766)
	Mean (SD)
Age (years)	46.2 (11.4)
Baseline Body Mass Index (kg/m^2)	29.1 (5.0)
Baseline Weight (kg)	84.0 (17.2)
Perceived Virtual Care Climate	4.7 (1.0)
Physical Activity Data (Baseline)	
Steps	11087 (3656)
Moderate-to-vigorous physical activity (minutes)	58 (36)
Physical Activity Data (six months)	
Steps	10850 (3345)
Moderate-to-vigorous physical activity (minutes)	71 (45)
Physical Activity Data (12 months)	
Steps	10905 (3450)
Moderate-to-vigorous physical activity (minutes)	77 (51)

To further test the model fit to the data, we performed the same analysis with the upper and the lower tertile of our sample (participants' characteristics available in Additional File 1), that is, the third of individuals that presented largest increases or decreases in PA outcomes from six to 12 months (Table 2). The model presented similar fit indices for MVPA. However, model fit improved slightly for Steps with a reasonable fit to the data of the upper tertile but the percentage of explained variance remained small and non-significant ($\chi2 = 40.867$, df = 20 [2.04], $p = .004$; CFI = 0.905; TLI = 0.786; RMSEA = 0.064 [0.35; 0.92]; SRMR = 0.066; $R^2 = 0.013$ [p = .47]).

Since our confirmatory method yielded poor results, we decided to take an exploratory approach to test our mediation model. According to Structural Equation Modelling literature, individual paths are multiplied across the model (Hayes, 2017; Kline, 2015), and this way, negative paths (in this case, controlled motivation) cancel out positive impacts (that is, autonomous motivation). We also decided to remove the global composite of BPN satisfaction due to its complex structure of congregating three different constructs in one single score. Therefore, we tested the same model removing BPN composite and separating control from autonomous motivation using two model variations: a) influence of

Table 2
Model fit indices for Model 1 and Model 2.

Tested models	χ2/df	CFI	TLI	RMSEA	SRMR	R^2
Steps						
Model 1 – all participants	5.86*	.881	.733	.080 (.066; .094)	.071	.010
Model 1 – Upper Tertile	2.04*	.905	.786	.064 (.035; .092)	.066	.013
Model 1 – Lower Tertile	3.13*	.876	.721	.091 (.066; .117)	.080	.038
MVPA						
Model 2 – All participants	6.23*	.873	.715	.083 (.069; .097)	.072	.008
Model 2 – Upper Tertile	2.63*	.886	.744	.080 (.054; .106)	.076	.003
Model 2 – Lower Tertile	3.47*	.846	.653	.098 (.074; .124)	.087	.001

Note: * Significant level $p < .05$; MVPA: Moderate to vigorous physical activity; χ2/df = Chi-square divided by the degrees of freedom; CFI: Comparative fit index; TLI: Tucker-Lewis index; RMSEA: Root mean square error of approximation; SRMR: Root mean square residual; R^2: Coefficient of determination.

autonomous motivation variables on self-regulatory variables and subsequent behavior (Figure 2); and b) influence of controlled motivation related variables on self-regulatory variables and subsequent behavior (Figure 3). Indeed, both models presented good fit as showed in Table 3. Except for the controlled motivation mediation model with MVPA as outcome, all other models increased goodness-of-fit depending on the tertile in which they were tested. The autonomous motivation models presented better fit in the upper tertile samples (best PA changes) and the controlled motivation models presented better fit in the lower tertile samples (worse PA changes). However, the percentage of the outcome variables variance explained by each model remained negligible. Adding the BPN satisfaction variable to the model yielded inferior results.

After establishing the final model, we proceeded with the test of the configural invariance across countries. However, both the chi-square difference test and the CFI differences between the constraint and the unconstrained models suggested that our models were variant at the country level (for full details please refer to Additional File 2). To account for this influence, we rerun all analysis controlling for the variable country. Results are presented in Table 4. The changes in goodness of fit indexes and in path coefficients were minimal.

For a final step, we analyzed the direct and indirect effects of the simpler models controlling for country. No total indirect effects were found from *Virtual Care Climate* to Steps or MVPA. However, we found specific indirect effects on both models. Considering the mediation model including the autonomous motivation variables, *Intrinsic goals* were positively and indirectly associated with *Action Control* ($b = .037$, $p = .001$), *Action Planning* ($b = 0.046$, $p = .001$), and *Coping Planning* ($b = 0.047$, $p = .001$) via *Autonomous Motivation*. Considering the mediation model including the controlled motivation variables, *Extrinsic Goals* were negatively and indirectly associated with *Action Control* ($b = -0.030$, $p = .001$), *Action Planning* ($b = -0.020$, $p = .056$), and *Coping Planning* ($b = -0.030$, $p = .001$) via *Controlled Motivation*.

One indirect effect was found in the autonomous motivation model with Steps as outcome (Additional file 3), where *Autonomous Motivation* was positively and indirectly associated with increased number of *Steps*, via *Action Control* ($b = 0.016$, $p = .047$). The controlled motivation model did not wield indirect effects for either outcome. Testing the model with the upper and lower tertile of the sample did not improve these results (data not shown).

3. Discussion

This was one of the first attempts to investigate a pre-defined integrative logic model that includes SDT-related motivational variables (*Basic Psychological Needs*, *Goal Content*, and *Behavioral Regulations*) and self-regulation variables (*Action Control*, *Action Planning* and *Coping Planning*) to explain long-term device-measured changes in PA (Steps and MVPA) in the context of a digital behavior change interventions for weight loss maintenance. Despite promising evidence from previous systematic reviews suggesting increases in PA outcomes via these mediators in obesity-related lifestyle change interventions (Teixeira, Carraça, et al., 2015), the model presented poor fit to the data with limited and non-significant predictive power either for Steps or MVPA. When examining the mediation model through three hypothesized consecutive timepoints - zero, six and 12 months - we found no direct or indirect effects on long term increases in number of Steps and in time spent in MVPA (six to 12 months) via motivational and self-regulatory mediators.

These results may be explained by the complexity of psychological model which are needed to explain complex behaviours such as PA. Also, due to this complexity, researchers try to create *ad-hoc* composite scores of the psychological scales to simplify models by reducing the number of variables in their mediational models. However, this reduction only reinforces the need to include other "new" variables to increase the predictive capacity of the conceptual model. For instance, we included a composite score of Basic Psychological Needs Satisfaction scale that conceptualizes three different sub-scales.

Having this in mind, we followed an exploratory approach to further analyze our conceptual model using a more parsimonious mediational path considering the Controlled Motivation independently of Autonomous Motivation, and by removing Basic Psychological Needs

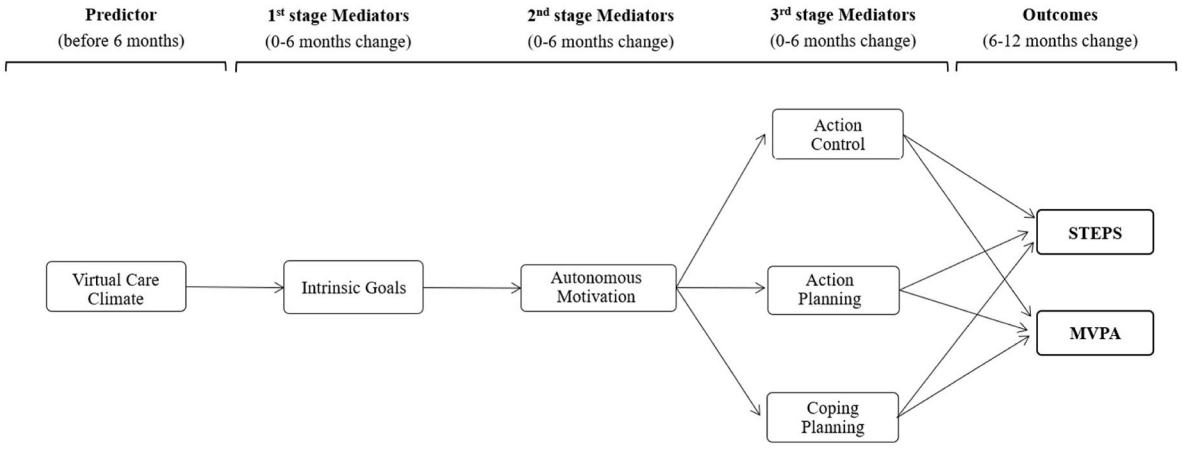

Figure 2. Autonomous motivation model
Notes. MVPA: Moderate-to-Vigorous Physical Activity.

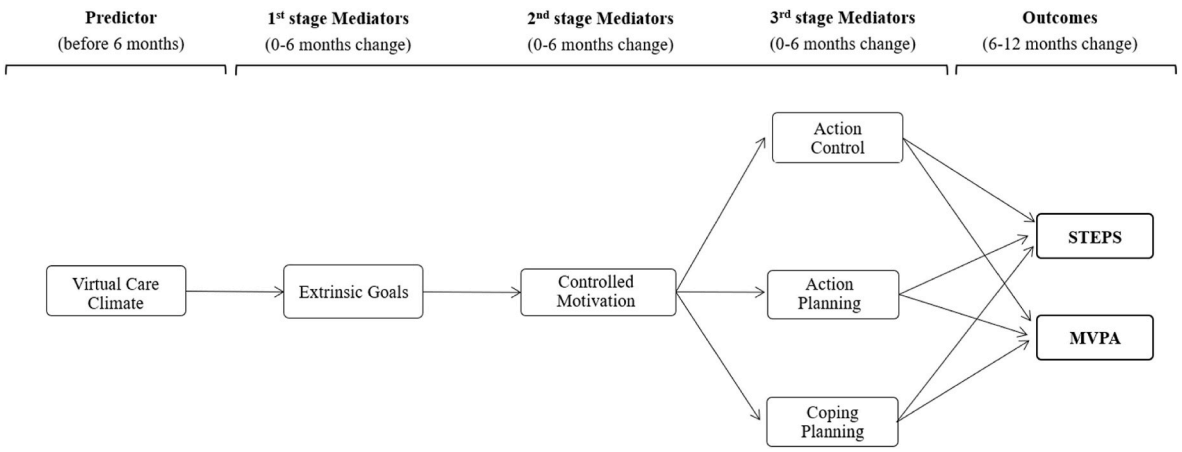

Figure 3. Controlled motivation model

Table 3
Model fit indexes for Model 3 and Model 4.

Tested models	χ2/df	CFI	TLI	RMSEA	SRMR	R^2
Steps						
Model 3 AM – All participants	4.44*	.944	.869	.064 (.043; .086)	.054	.010
Model 3 AM – Upper Tertile	0.91	1.00	1.01	.000 (.000; .066)	.042	.038
Model 3 AM – Lower Tertile	2.18*	.906	.782	.068 (.026; .109)	.063	.012
Model 3 CM – All participants	2.77*	.965	.919	.048 (.026; 0.71)	.041	.010
Model 3 CM – Upper Tertile	1.33	.987	.970	.036 (.000; .084)	.040	.038
Model 3 CM – Lower Tertile	0.78	1.00	1.05	.000 (.000; .059)	.031	.012
MVPA						
Model 4 AM – All participants	4.51*	.937	.852	.068 (.047; .089)	.055	.008
Model 4 AM – Upper Tertile	1.56	.970	.930	.047 (.000; .092)	.055	.001
Model 4 AM – Lower Tertile	3.19*	.890	.744	.093 (.056; .132)	.072	.003
Model 4 CM – All participants	3.24*	.956	.898	.054 (.033; .077)	.042	.008
Model 4 CM – Upper Tertile	2.46	.931	.838	.076 (.036; .116)	.056	.001
Model 4 CM – Lower Tertile	2.21	.928	.832	.069 (.027; .110)	.053	.003

Note: * Significant level $p < .05$; AM: autonomous motivation mediation model; CM controlled motivation mediation model. MVPA: Moderate to vigorous physical activity; χ2/df: Chi-square divided by the degrees of freedom; CFI: Comparative fit index; TLI: Tucker-Lewis index; RMSEA: Root mean square error of approximation; SRMR: Root mean square residual; R^2: Coefficient of determination.

Satisfaction composite score from the model. These changes increased the model fit substantially but with no additional increases in explained variance. Therefore, even when achieving very good fit indices, our model was not able to explain the variation in our sample, neither increases nor decreases in PA outcomes.

Simply put, our model confirmed that the theoretical relationships between the tested mediators were once more confirmed, but that despite the complexity of the logic model, including three different phases of mediation and multiple variables ranging from distinct aspects of motivation to distinct aspects of behavioral regulation, the predictive capacity of our current models were negligible when considering device-measured PA. Still, the level of explained variance would substantially increase if past behaviour was considered in the model, but our focus was solely on testing psychological mechanisms.

Table 4
Model Fit Indexes for both Model 3 and Model 4 after controlling for Country.

Tested models	χ2/df	CFI	TLI	RMSEA	SRMR	R^2
Steps						
Model 3 AM	4.43*	.947	.840	.067 (.047; .089)	.051	.215
Model 3 CM	2.72*	.971	.914	.047 (.025; 0.70)	.038	.220
MVPA						
Model 4 AM	4.78*	.942	.825	.070 (.050; .092)	.052	.229
Model 4 CM	3.26*	.963	.888	.054 (.033; .077)	.039	.229

Note: * Significant level $p < .05$; AM: autonomous motivation mediation model; CM controlled motivation mediation model. MVPA: Moderate to vigorous physical activity; χ2/df: Chi-square divided by the degrees of freedom; CFI: Comparative fit index; TLI: Tucker-Lewis index; RMSEA: Root mean square error of approximation; SRMR: Root mean square residual; R^2: Coefficient of determination.

However, our findings are in line with results from other similar studies. Indeed, findings from a meta-analysis of SDT-based interventions in health behavior change provided significant but small effect of SDT variables on health behaviors (Sheeran et al., 2020). For instance, Murray and colleagues (Murray et al., 2020) found effectiveness of a behavioral intervention on targeted mediators but these changes were not translated in increases in device-measured PA behavior (however in this case using a Yamax Digitwalker CW-701 pedometer). Also, Sebire et al. (2011) found limited predictive capacity of a simpler SDT based mediation model on device measured MVPA minutes ($R^2 = 0.07$).

These findings may reflect the complexity of human behavior (Sheeran & Webb, 2016). PA is a complex, dynamic, and multifaceted behavior. The self-regulation construct itself in which these mechanisms of action are based is still evolving (Sheeran & Webb, 2016), and other authors have proposed new and more advanced approaches of conceptualization (e.g., Eisenberg et al., 2019). Also, the mechanisms of action that are in place to *start* the behavior may be different from those that are required to *maintain* the behavior (Rothman, 2000; Rothman, Baldwin, Hertel, & Fuglestad, 2004). Nevertheless, evidence of a relationship between these theory-driven mechanisms of action and *change* in PA behaviour was not evident.

One could argue against the proposed sequence of the mediators of our logic model, but it is hard (if not impossible) to discern what comes first, autonomous motivation or intrinsic goals? Action control or basic psychological needs? But, as eloquently stated by Hayes (Hayes, 2017) it is the researcher that interprets statistical procedures, and our analysis confirmed the associations between these psychological mechanisms based on existing evidence (Hagger & Chatzisarantis, 2014; Hagger & Luszczynska, 2014; Lakerveld et al., 2020; Sniehotta, 2009; Sniehotta, Scholz, & Schwarzer, 2005; Teixeira, Mata, Williams, Gorin, & Lemieux,

2012). Though, to address this methodological problem, new techniques of psychometric assessment with repeated measures overtime should be developed to account for the fluctuation through time and the dynamic loops that are not captured in discrete 6-month time-points assessments typical of RCTs designs. Examples of such procedures are the ecological momentary assessments, as discussed by Short et al. (2018).

Therefore, advancements in technologies that objectively assess PA behavior that are automatic and could provide different types of information than self-reported measures (Loney, Standage, Thompson, Sebire, & Cumming, 2011) and may allow the measurement of new behavioral patterns not used yet in behavioral interventions. This may be a topic of concern, as past research analyzed the hypothesized intention-behavior gap by relying massively on self-reported PA measures, that are suggested to overestimate MVPA and underestimate sitting time (Cerin et al., 2016). Therefore, appropriate methods of repeated objective assessments of the actual health behavior are required and are pivotal for theory refinement (Stubbs et al., 2021), by providing new insight regarding the historically debated limited predictive capacity of behavior change theories (Kelly & Barker, 2016; Sheeran & Webb, 2016).

To this end, digitally enabled psycho-social assessments are predicted to be innovative in the field of human behavior change (Arigo et al., 2019; Wadden et al., 2020), and they may overcome some limitations of the classical timepoint specific intervention studies. Digital technologies enable collection of information from participants more often and are not strictly fixed to specific time points of assessment (continuously for six months) (Murray et al., 2020; Scholz, 2019; Sniehotta, Presseau, & Araújo-Soares, 2014). Furthermore, digitally enabled assessments may reduce participant burden with briefer and shorter scales.

It is also important to contextualize the high levels of MVPA found on our sample, far exceeding the international PA guidelines. However, one should consider that this sample include weight losers and weight loss maintainers that may need more PA to maintain their weight management goals (Yumuk et al., 2015). For instance, considering the literature on National Weight Control Registries, Santos et al. (2017) reported about 19% of weight losers enrolled in the Portuguese registry did between 450 and 800 min of objectively-measured MVPA per week, and with a much longer maintenance duration (average 28 months). Other example, Soleymani, Daniel, and Garvey (2016) presented data from the United States National Weight Control Registry where is reported that 90% of the individuals enrolled in this registry exercised, on average, about 420 min per week (i.e., 1 h per day). On the other hand, NoHoW participants are naturally more motivated than regular citizens due to i) their very recent weight loss (within the previous year), ii) for being included in a weight management focused research, iii) for having received new digital devices and psychological intervention specifically to increase PA levels.

3.1. Strengths and limitations

Following recent guidelines (Hagger et al., 2020), this study attempted to investigate putative mediators included in the NoHoW's logic model that could explain changes in device-measured long-term physical activity levels (six to 12 months). It is also one of the first attempts to assemble, in one single logic model, the multiple phases of behavioral regulation, combining both motivational and volitional constructs to explain long-term change in device-measured Steps and MVPA, using sound Structural Equation Modeling techniques.

Despite the suggested evidence of the dynamic influence between the motivational and the self-regulatory variables, these hypothesized mechanisms did not produce consistent impacts on behavior, as expected. The inspection of the coefficient paths confirmed the theorized relationships between the tested mediators but not between these and the actual device-measured PA behavior. We also tested the model with the upper and lower tertiles of our sample, and by specifying direct paths between behavioral regulations and outcomes, but no improvements were found (data not shown).

A limitation that may also be discussed is the influence of other variables not considered by the logic model (such as self-efficacy or social support, stress, emotion, cost, rewards) may have played an important mediating role (MacLean et al., 2015; T. Wang et al., 2019). Although this is a major concern when designing complex interventions, with broader theoretical scopes and multiple variables to assess, that involves time-consuming psychometric batteries of tests that increase participants' burden.

Another aspect to consider is the need for cross-culturally validated psychometric instruments when pooling data from different countries and cultures. Our study only managed to include one scale with sound cross-cultural validation, the Goal Content for Weight Management Scale (Encantado et al., 2021). Therefore, differences in constructs measurement may exist between countries that we were not able to test here. To account for these influences our final analyses were conducted controlling for the variable country, which produced residual differences in model fit and the relationships between variables. However, in future studies researchers may consider including larger subsamples for each different country to be able to test these potential differences further. Despite our total sample being relatively large (more than 700 participants) the fact that it was distributed across three different countries restrained the analysis at a country level for such a complex mediation model (about 250 participants in each country).

Also, because the Virtual Care Climate Questionnaire must be answered retrospectively after the intervention ends, we must take into consideration as a limitation the recall biases that may arise and the difficulty in maintaining temporal precedence in the mediation model. One option we may suggest for future interventions to solve these problems would be to develop a measure of the intervention climate that is suitable to be used during the intervention. This way, the intervention climate could even be assessed at several time points to cover the entire duration of the intervention.

Future interventions may also build on the current analysis to better understand the relationships between motivational and self-regulatory variables. However, considering that the hypothesized logic model failed to explain the variance in device-measured PA change, future intervention designers may choose to elaborate on simpler logic models as suggested by Hagger et al. (Hagger et al., 2020). To isolate behavior change techniques and mediators in more simple logic models to test its effects on behavior could provide more precise insights on what works, for whom and how. It would also be of particular interest to include more frequent assessments of mediators and outcomes and/or tracking predictor-outcome relationships to provide insights on longitudinal fluctuations and causal sequences of impact. By following and monitoring these assessments it would be feasible to personalize the content of the intervention to each individual need to increase engagement with the intervention and provide extra support (Ryan, Dockray, & Linehan, 2019; Stubbs et al., 2021). Also, it would be beneficial to track the dynamics of energy balance behaviors during the course of behavioral interventions (Stubbs et al., 2021), using electronic tracking behavior and ecological momentary assessments to collect intensive longitudinal data that allow for between and within person complex modeling methodologies (Dunton, Rothman, Leventhal, & Intille, 2021).

These approaches may help to understand why people lapse and relapse or disengage from long-term weight loss maintenance interventions (Stubbs et al., 2021). To target personally relevant, robustly tested and theory-based components of digital behavior change interventions may help prevent disengagement and improve the success of future weight loss maintenance. Other limitation that should be considered is attrition bias, as only about half the NoHoW trial participants provided 12-month psychometrics and behavioral data. Participants that are more comfortable and value the use of digital technologies may endure longer than those who are less engaged with these new devices and technologies. This phenomenon may also result in sample

selection bias, as the former profile of persons are more likely to sign up for participation in a digital intervention trial than the latter profile. Another caveat concerning our analysis comes from the limitations underlying the current activity monitor technology (i.e., Fitbit Charge 2) that do not present yet an optimal accuracy in PA measurement, but overestimate steps and underestimate MVPA (Mikkelsen et al., 2020).

Therefore, due to the limitations of the sample regarding model measurement variations between countries and the specificities of our sample (weight-loss maintainers), the generalization of the current results should be done carefully. Physical activity is a complex behaviour and some of its mechanisms may be culturally sensitive; this highlights the importance of designing more such studies, using psychometrically sound and cross-culturally validated instruments.

4. Conclusion

The current study tested a theory-based logic model in the context of a digital weight loss maintenance intervention to explain long-term PA outcomes (steps and MVPA) using putative motivational and self-regulatory mediators. Using a parsimonious approach, we tested the Autonomous Motivation and the Controlled Motivation mediational models independently yielding excellent model fit. However, the models were not invariant across countries and did not perform as intended, presenting only residual explanation of the PA outcomes variance. Also, no direct or indirect effects were observed and only *Action Control* directly predicted increases in number of Steps. These findings suggest that current models and theories of behavior change in the context of weight loss maintenance may need further refinement to explain changes in device-measured PA. The gap between psychological mechanisms and actual behavior may widen up with the increased precision of new objective methods of behavior assessment. Therefore, as behavioral scientists, we should think about Thomas Kuhn's argument: are psychologists and behavioral scientists trying to solve behavioral problems or are they "inadvertently" trying to solve theoretical puzzles?

Authors' contributions

RJS, BLH, PJT, FFS, and GH conceived the NoHoW project. MMM, ALP, PJT, and GH designed the digital intervention. All authors contributed to the development of the content and functionalities of the digital intervention. RO, JT, SL, DS, MMM, ALP, MJG, GH, and IS contributed to the data handling and statistical analysis. MMM, ALP, JE, MJG, and IS drafted the manuscript. All authors reviewed and approved the manuscript.

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Declaration of competing interest

RJS consults for Slimming World through Consulting Leeds, which is a wholly-owned subsidiary of the university of Leeds. Slimming World was a former partner in NoHoW. MMM and GH has previously consulted for Slimming World, who was a former partner in NoHoW project. All other co-authors have no conflicts of interest to declare.

Data availability

Data is publicly available on OSF platform

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2022.102314.

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