



# Survey on virtual coaching for older adults

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## Abstract

Virtual coaching has emerged as a promising solution to extend independent living for older adults. A virtual coach system is an always-attentive personalized system that continuously monitors user's activity and surroundings and delivers interventions – that is, intentional messages – in the appropriate moment. This article presents a survey of different approaches in virtual coaching for older adults, from the less technically supported tools to the latest developments and future avenues for research. It focuses on the technical aspects, especially on software architectures, user interaction and coaching personalization. Nevertheless, some aspects from the fields of personality/social psychology are also presented in the context of coaching strategies. Coaching is considered holistically, including matters such as physical and cognitive training, nutrition, social interaction and mood.

## Keywords

coaching intervention, coaching strategy, context-awareness, interface modality, self-monitoring

## Introduction

Most of the previous attempts to define virtual coach systems (VCSs)<sup>1</sup> have been so generic that many systems, devices or programmes could be considered. We share Siewiorek's<sup>2</sup> more demanding VCS definition, presented in the abstract of the article. This work contributes by:

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1. Collecting the state-of-the-art of technological and methodological approaches for a VCS for older adults. Information about the systematic review can be found in the supplementary material.
2. Presenting the design space of a VCS (Supplemental Figure 1).
3. Proposing implementable novel approaches and categorizing them within the proposed design space (Supplemental Figure 2).
4. Considering validation as a crucial part in the development of a VCS. Last section reviews the different methodologies.

## VSC components

This article contributes with a proposal of the design space of VCSs. The purpose is to provide a common design space to refer to in the forthcoming publications.

This analysis started following Ding et al.'s<sup>1</sup> work, which defined the components of virtual coaching interventions (Supplemental Figure 3). According to Siewiorek's<sup>2</sup> definition, a VCS must be able to deliver interventions. Ding et al.<sup>1</sup> defined four components for virtual coaching interventions: self-monitoring, context-awareness, interface modality and coaching strategy. These components respond to the questions of what message to deliver and when and how to intervene the user.

This article compared Ding et al.'s<sup>1</sup> components with literature, to confirm and validate their presence within the design space of a VCS. Bibliography reviews (Supplemental Tables 2 and 4 to 7) confirm components' presence in the design space of a VCS. Nevertheless, the bibliography compiled in this article (Supplemental Table 6) points out the convenience of adding a fifth component to the design space. It will be called coaching intervention, and it defines the purpose of the intervention – that is, suggesting an activity, reminding something and so on. Supplemental Figure 1 represents the design space of VCSs defined and proposed in this work, as well as the dependencies between the components. VCS's five components are:

1. Self-monitoring: sensor-based technology for automatic user and environmental data collection.
2. Context-awareness: computational component that infers contextual information from user-related data, extracted by self-monitoring and by integrating additional information through external databases.
3. Interface modality: interaction method between the user and the VCS.
4. Coaching interventions: short-term actions of the virtual coach following a coaching strategy, for example, reminding medicine intake or suggesting physical training exercises.
5. Coaching strategy: guidelines for optimal user-tailored coaching, dynamically adapting to user's need, performance and progress. That is, it personalizes and adapts the coaching message considering the contextual information, which includes self-monitoring data, and the interfaces and coaching interventions available.

## Self-monitoring

This component uses sensor-based technology to automatically collect data from the user and her or his environment, objectively and comfortably.

Self-monitoring has some limitations for subjective data collection. Self-report data is the best choice in these cases. However, if possible, self-monitoring should be used for data extraction (see Supplemental Table 3). Information and communications technology (ICT) platform can be used for the evaluation of self-monitoring devices.<sup>3</sup>

Sensor-based technology can be integrated into a wearable device or placed in an environment's surroundings creating a sensorized environment. This article follows a technological main categorization, instead of user-centred.<sup>4</sup> Here, a wide variety of sensors are considered. Supplemental Table 2 compiles those used in VCSs.

## *Wearable devices*

Wearable devices or wearables refer to electronic devices that can be worn. They are mostly small, lightweight and discreet, pretending to be an accessory, for example, wristband,<sup>5</sup> or being hidden under clothes, for example, chest belt.<sup>6</sup> There are different packaging formats available to address diverse user preferences, including headsets.<sup>7,8</sup>

Older adults could perceive an added value in their use.<sup>4</sup> However, wearables' major feature is their ability to connect to the Internet and permit network-device data exchanging – Internet of things. Despite their benefits, wearables' usage implies some drawbacks, such as user's discomfort while wearing, recharging, data privacy concerns, indirect data access, black-box-like algorithms, data standardization issues and unverifiable wearable usage.<sup>4</sup>

This section categorizes wearables, depending on their purpose of usage, into affective, cognitive, physical and clinical. The different categories of wearables may overlap since they all monitor physiological metrics in the end.

*Affective wearables.* Affective wearables can recognize user's affective patterns, for example, expressions of emotion, a strained voice and a change in autonomic nervous system activity.<sup>9</sup>

Application examples include lifelogging technology<sup>10</sup> and estimation of stress,<sup>11</sup> sleep and activity levels.<sup>12</sup>

*Cognitive wearables.* Cognitive wearables measure user's cognition, the mental process of understanding through thought, experience and senses.

Automatic measurement of the cognitive capacity is a difficult task. Cognitive Kit<sup>13</sup> combines self-monitoring with self-reporting, with positive results in major depressive disorder cases.<sup>14</sup>

*Physical wearables.* Physical wearables<sup>15</sup> measure physical activity through direct activity data extraction, vital signs' analysis or both.<sup>16,17</sup> Some are smart watch,<sup>18</sup> smartphone's accelerometers monitor daily physical activity of older adults,<sup>19</sup> localization through global positioning system (GPS),<sup>20</sup> Bluetooth, Wi-Fi or Ultra-Wideband.<sup>21</sup> A promising solution approach is Wi-Fi fingerprinting.<sup>22</sup>

For validation of extracted data, ActiGraph GT3X is the gold standard, being capable of monitoring daily life activities of different age groups.<sup>19</sup>

*Clinical wearables.* These wearables provide clinically relevant information, usable for diagnostic or predictive purposes. Applications for older adults can describe user's well-being through, for example, sleep quality,<sup>12</sup> body balance or frailty.<sup>23</sup>

Body balance information allows evaluating older adults' ability to carry instrumental activities of daily living and developing fall detection and prevention responses.<sup>24</sup>

Frailty serves in older adults as a prognostic factor of disabilities, institutionalization/hospitalization and mortality.<sup>25</sup> Technological approaches focus on Fried's clinical test<sup>26</sup> to measure frailty through gait parameters, physical activity, strength and balance.<sup>25,27</sup> Cognitive frailty should be measured, as well.<sup>28</sup>

## Sensorized environments

Sensorized environments are spaces where sensors have been deployed, for example, house. There are two types: general purpose and smart furniture and objects.

*General purpose home sensors.* They gather four data types: physical, clinical, affective and cognitive.

*Physical data gathering.* It is mainly carried out through computer vision approaches. Microsoft Kinect<sup>29</sup> tracks user's presence and motion. Kinect's manufacturing has been abandoned but its detection capacity has demonstrated that similar alternative technology can be developed, for example, OpenSim.<sup>30</sup>

Acoustic sounds retrieved through a wireless sensor network provided footstep location.<sup>31,32</sup>

Some research focuses on fall detection.<sup>24</sup> Gait pattern variations can be correlated to physical, mental or cognitive health variations.<sup>30,31</sup>

*Clinical data gathering.* Approaches can sense frailty, pollution, smell, epileptic seizure and so on.<sup>25,33-35</sup>

*Affective data gathering.* Emotion recognition capacity is vital for an empathic VCS. Humans express emotions through verbal – speech and writing – and non-verbal signals – hand and body gestures and facial expressions.<sup>36-38</sup> Emotion recognition accuracy will improve when exploiting data from various expression ways.<sup>39</sup>

Accompanying people's face identification improves tracking older adults' social life.<sup>40</sup>

*Cognitive data gathering.* Older adults can suffer a transitional stage between normal cognitive aging and dementia, called mild cognitive impairment. It can hinder the completion of complex daily tasks.<sup>41</sup> Dawadi et al.<sup>41</sup> used infrared motion detectors and magnetic door sensors, extracted 35 activity-related features and used them to feed the machine learning algorithms.

Selker et al.<sup>42</sup> developed a system for cognitive decline assessment through walking times, walking speed and activity amount.

*Smart furniture and objects.* These are employed to gather user's both physical – activity level – and clinical information, for example, sleep, nutrition, snoring, heartbeat and oximetry.

*Smart furniture.* Detected smart furniture includes mostly tables, then chairs and finally individual cases of mat, mattress, floor, shelf, sink and board.

Smart tables' application involves nutritional intake monitoring,<sup>43</sup> multiple objects' identification and tracking<sup>44</sup> and monitoring the use of the table.<sup>42</sup>

Smart chairs monitor stress levels – via heart and breathing rates<sup>45</sup> – or activity level – through body weight, body temperature, heart rate, blood oxygen saturation and blood pressure.<sup>46</sup>

Smart mats and mattresses monitor sleep quality through respiratory rate and heart frequency.<sup>47</sup> Andoh et al.<sup>48</sup> adds snoring and body movements.

The smart floor<sup>48</sup> tracks location, the smart shelf<sup>49</sup> monitors in-stock products, the smart sink<sup>50</sup> controls temperature and water flow and the magnetic board<sup>51</sup> tracks physical activity accessories' usage.

*Smart objects.* Smart objects are varied such as toothbrush and mirror,<sup>52</sup> cups,<sup>53,54</sup> a bottle,<sup>55</sup> a spoon<sup>56</sup> and a walking stick.<sup>57</sup>

## Context-awareness

Context is crucial in VCSs. First, it can reduce the complexity of the problem to solve, by decreasing user choices and reducing the search space. Second, it allows adapting to the user's state.

Context is captured through self-monitoring and external databases – weather, electronic health record (her) and so on. Context is based on information about the current status of entities – people, places, things or devices – in the environment, including the location, time, activities and preferences of each entity.<sup>58</sup> Eventually, it is proven that a user's responsiveness to an intervention highly depends on her or his current tasks, in addition to other factors such as emotional state and the modality of the intervention.<sup>58</sup> Context-awareness means that one can use contextual information.<sup>59</sup> Context-aware systems are characterized by their capacity to extract, interpret and use contextual information for information and services' provision and to adapt its functionality to the current context of use.<sup>58,59</sup> Abowd et al.<sup>58</sup> defined the core context-aware features that context-aware applications may support (1) presentation of information and services to the user, (2) automatic execution of a service and (3) tagging context to information for later retrieval.

Main components of a context-aware system are:

1. Context providers and context-aware services<sup>60</sup>: context providers acquire data from different sensors through direct sensor access, middleware or context servers.<sup>61</sup> Context-aware services provide relevant services based on acquired contextual data. The concept of service integration can be constructed in a service-oriented architecture.<sup>62,63</sup>
2. Context-aware computing: a ubiquitous software component that adapts the system's functions depending on the context information.<sup>64</sup>
3. Context modelling: the formulation of a system that interprets and understands several system nuances.<sup>65</sup> Nykänen and Rodriguez<sup>61</sup> detected the major strategies for context modelling, including key-value, object-oriented and ontology-based models. There is not a commonly agreed standard for modelling, but ontology-based models seem to offer many desirable properties such as dealing with incomplete or partially understood information and domain-independent modelling.<sup>66</sup> Standard representation of context data in context-aware systems can be built upon semantic web metadata standards, such as Resource Description Framework (RDF) and OWL.<sup>67</sup> There are many modelling approaches: SNN,<sup>61</sup> SOCAM,<sup>65</sup> ASSL<sup>65</sup> and Process Mining.<sup>65</sup>

Despite the technological advancements and research results, the realization and the role of complex context-aware computing are not clear in application ecosystem(s).<sup>61</sup>

Literature collects different attempts to define context.<sup>58</sup> Loureiro and Rodrigues<sup>68</sup> provided the easiest definition where context refers to any information that characterizes the situation of an entity – that is, a person, place, or object relevant to the user–applications interaction. For Loureiro and Rodrigues,<sup>68</sup> the primary context pieces for characterizing a situation of an entity are location – where, identity – who is the older adult with, activity – what and time – when. Primary context types act as indices into other sources of contextual information to find secondary context pieces for that same entity, for example, email address. Secondaries are obtained by combining different primary context types and/or integrating external database information, for example, weather. Supplemental Table 4 shows how context has been used in VCSs.

## Interface modality

Interface modalities define the interaction path between the user and the system. Information is presented to users through interface devices and user interfaces (UIs). The presentation method strongly impacts the communication interaction and may affect the usability and user's adherence towards the system.

Following review provides a broad point of view about interface modalities. Supplemental Table 5 collects which and how have been employed in VCSs.

The UI is the space where bidirectional human-machine interactions occur: from human to machine (H2M), for example, to control the system or from machine to human (M2H), for example, to provide information to the user. UIs are supported by interface devices. These can be varied, for example, smartphone and VR headsets, providing different possibilities to adapt to user preferences and system requirements.

Older adults' adherence will increase if VCS's interface modality is intuitive. Interface devices' usage intuitivity can increase by integrating context-aware computing techniques. For example, handheld interface devices as smartphones adjust the UI design in real time to the orientation of the visualization screen. Natural user interfaces (NUIs) are the intuitive UI option. NUIs replace device-based control by gestural movements, promoting direct, intuitive and natural interaction ways.<sup>68</sup> Multi-touch and gestural computing are among the most often used technologies for implementing NUIs.<sup>68</sup> Speech and handwriting are additional examples. Part of our natural interaction manner with our environment is through senses: sight, hearing, touch, smell and taste. Based on the NUI concept, UIs can be categorized as vision-based graphical UIs (GUIs), audio-based voice UIs (VUIs) and sound UIs (SUIs), tactile UIs (TUIs), olfactory UIs and gustatory UIs.

GUIs provide an immediate visual feedback of user's actions, facilitating the learning stage. GUIs' advantages' exploitation strongly depends on the interface device employed. Innovative GUIs based on VR, AR or holograms may require obtrusive interface devices: headsets, smart glasses or projectors. So, tangible UIs<sup>69</sup> are recommended.

VUIs consist of the voice application system, in charge of allowing speech-based interactions: Mayer et al.<sup>70</sup> showed that participants perform better when the voice is human rather than machine generated.

SUIs rely on human's capacity to extract passively information from sounds and associate it to actions. For example, when we hear the alarm bell in a building, we could relate it to a fire evacuation. Bickmore et al.<sup>71</sup> recommends not using impolite audio alert tones. In contrast, text warning messages can be easily ignored.<sup>72</sup>

TUIs centre on haptic feedback, which include pressure, vibration, heat and pain<sup>73</sup>: thermal stimulation for nervous system responsiveness quantification<sup>74</sup> and sensory substitution.<sup>75</sup> Sensory substitution is useful for people suffering from balance disorders and loss/reduction of visual, vestibular and somatosensory information. Smartphones might also serve this purpose.

Olfactory and gustatory UIs may be the most difficult and complex ones to develop since humans depend on chemicals to experiment these senses. Research on these two interface modalities was boosted by VR applications, looking for innovative ways to enhance immersion feelings. Olfactory sense stimulation can be used for warning interventions, for example, food burning, or lifelogging applications,<sup>76</sup> gustatory UIs to stimulate appetite in older adults.<sup>77</sup>

Middleware interfaces are not within the scope of this review. Some commercial and open source approaches for IoT devices are OpenIoT,<sup>78</sup> MiddleWhere,<sup>79</sup> Hydra,<sup>80</sup> FiWare<sup>81</sup> and Oracle Fusion Middleware.<sup>82</sup>

## Animated agents

They provide a mixed UI modality. Animated agents create stronger user-system bonds, increasing adherence. Often, they act as virtual coaches.

Agents' embodiment varies from geometrical shapes to human-like characters, including holograms.<sup>83</sup> Agents' appearance and expressiveness relies on user preferences. For example, a 3D human agent with blinking eyes is rated as more intelligent than geometric shapes or caricatures.<sup>84</sup>

Animated agents can have non-verbal and/or verbal conversational capacity. Non-verbal is expressed through facial expressions and gestures. Non-verbal expressiveness and appearance define emotional and relational skills, increasing adherence.<sup>85</sup>

Verbal animated agents express text-based or voice-based messages. A talking face increases user adherence.<sup>86</sup>

Regarding non-verbal communication, opinions are varied: Moreno et al.<sup>87</sup> states that non-verbal communication does not improve UIs and Atkinson<sup>88</sup> defends that non-verbal presentation enhances learning.

## Coaching interventions

This section describes a new component proposal, not considered by Ding et al.<sup>1</sup> The literature review compiled in VCS state-of-the-art (see Supplemental Table 6) and this section provides a formulation for this contribution. Coaching interventions refer to short-term actions delivered through intentional messages. They define the purpose of the message, for example, reminding something.

User's interruption level and intervention's urgency level can be estimated through activity-related contextual information.<sup>89</sup> That is, there is no need of delivering a medicine-intake reminder while the user is talking on the phone, for instance. The intervention could be postponed until the user hangs up the phone.

Based on literature analysis, this article classifies interventions as reminders, warnings, recommendations, motivational and teaching. That is, VCS's behaviour has two main functions: assisting – through reminder, warning or recommendation interventions – and empathizing with the user – via motivational interventions.

## Reminders

Reminders reinforce the cognitive abilities of users. Older adults with cognitive impairment such as memory loss would be benefitted by an adaptive software-based personal reminder system. Some reminder approaches go beyond the context-based reminder delivery by estimating parameters such as forgetting probability of the user and the reasons for forgetting.<sup>86</sup> Zhou et al.<sup>89</sup> reviewed different factors that could influence the design and framework selection for reminder systems. Reminders are classified into two groups<sup>90</sup>:

1. Scheduling aids: for personalized daily fixed time activities' prompting. Different information can be used for triggering delivery<sup>89</sup>: time, location, activity and complex context. An application example is a medicine intake reminder system,<sup>91</sup> which tells when and how to take the medicine.
2. Instructional cueing aids: for subjects' guidance through sequential processes that once were known but are currently forgotten.



This article contributes with an additional category:

3. Activity accomplishment aids: for accomplishment of forgotten initiated daily tasks that remain unfinished. Unlike scheduling aids, activities are not subject to fixed times. Application examples include a smart reminder system (SRS) for in-home activities<sup>86</sup> and a gate reminder,<sup>92</sup> a home system in the front door that screens things users need to take before leaving home.

## Warnings

Warnings announce detected precarious situations, for example, when the oven remains turned on after use. For example, Boulos et al.<sup>93</sup> developed a wearable that communicates with caregivers in case of fall detection.

## Recommendations

Recommendation interventions offer suggestions concerning a non-urgent task that can cause, somehow, a negative impact on the user.

When defining these interventions, conclusions extracted from a workshop can be useful<sup>94</sup>: (1) delivery time must be adaptable to older adults' routine activities' time and (2) older adults require different recommendation types depending on the daytime. Hammer et al.<sup>51</sup> differs at least two types: daily routine-targeted and stimulators. First ones suggest the best time and/or place for a daily activity task. Stimulators boost activities out of the daily agenda, for example, meditation exercising. For computational implementation, tools such as LensKit recommender toolkit<sup>90</sup> and Drools<sup>95</sup> could be used.<sup>96</sup>

## Motivationals

Motivational interventions foster positive behaviour by cheering and guiding the user to overcome challenging situations.

Behaviour change inducement requires the employment of evidence- and psychology-based behaviour change strategies, discussed in the next section. This explains why motivation is categorized according to the self-determination theory (SDT)<sup>97</sup>:

1. Extrinsic: drives behaviour changes through external rewards, for example, scoring or social recognition. Gamification or serious games are an easy example where external rewards are used. During implementation, it is relevant distinguishing different reward types, for example, there are eight types in gamification,<sup>98</sup> and rewarding methods, for example, De Carvalho and Ishitani<sup>99</sup> compiled motivation guidelines for serious games for older adults. Older adults' preferences should be also contemplated. For example, Herpich et al.<sup>94</sup> collected preferences about rewarding the accomplishment of lifestyle recommendations.
2. Intrinsic: refers to behaviour change driven by internal rewards. For example, the satisfaction of taking self-care. P-creativity<sup>100</sup> is an innovative implementation method. It employs curiosity in novel and valuable concepts/designs/artifacts as a motivational engine. Grace et al.<sup>100</sup> developed an intrinsic motivation-boosting engine in a framework called personalized curiosity engine (PQE).

Concluding, intrinsic motivation is the core point for healthy aging promotion.



## Teaching

These teach users new skills. Older adults may face new challenges while they age. Learning how to face them could be a key factor to ensure their well-being. Skills could include stressors' management and education in training exercises or clinical awareness.

## Coaching strategy

Coaching strategy states the plan of actions or guidelines to maximize user's potential<sup>101</sup> and offer context-aware personalized coaching. The guidelines are grounded on contextual information, coaching interventions and available interfaces. This component can be identified in any VCS. Nevertheless, the implementation methods are diverse. This section focuses on the reasoning and decision-making ability requirements of VCSs. These can be provided through four strategies: clinical decision support systems (CDSSs), ecological momentary assessment (EMA) and intervention (EMI), behaviour change theories (BCTs) and models (BCMs) and clinical guidelines.

CDSS, EMA and EMI are more technology-centred. EMA and EMI are complementary, so usually they are not independently understood or explained. Remaining two strategies focus on action plan guidelines' definition. These strategies provide adaptivity to the VCS. EMA allows assessing the user in near real time. BCTs, BCMs and the clinical guidelines are employed to define the knowledge and evidence-based action plans. A CDSS is the decision-making engine, which provides a recommendation considering user-related data and the possible action plans. By last, EMI permits intervening on the older adults near to real time.

The four strategies can be implemented into the same system. Supplemental Figure 4 reflects the relationship between them. Supplemental Table 7 summarizes strategies in VCSs.

## Clinical decision support systems

A CDSS is a type of computerized information system for supporting decision-making tasks.<sup>102</sup> According to Sim et al.,<sup>103</sup> a CDSS is a software for aiding in clinical decision-making processes: it matches computationally patient's characteristics with computerized clinical knowledge base, to provide tailored recommendations or assessments to the user. That is, a CDSS relies on its clinical knowledge and reasoning ability. This converts CDSSs into a safe, reliable and efficient approach for in-home self-care. Pursuing an empathic and encouraging virtual coach, the CDSS may help the coach intervene using the appropriate intervention and interface depending on the context. For example, use a softer voice when the user is sad or remind picking up the laundry through visual interfaces if the user is talking on the phone. In addition, CDSSs may provide personalized health-care recommendation interventions to the user, for example, physical exercises. Some articles omit 'clinical' and use DSS.

Holsapple<sup>104</sup> presented a generic architecture for CDSSs. Marschollek<sup>105</sup> presented a state-of-the-art in CDSSs for in-home medical healthcare or patient support. It defined a set of requirements and properties to assess and categorize them. We consider that some requirements should be added: real-world data (RWD)-based training, big data management capacity and considering user preferences and context.

Marschollek<sup>105</sup> did not consider these features: dynamism<sup>102,103</sup> and intelligence.<sup>106</sup> Dynamism refers to CDSS's necessity to adapt to users' dynamic behaviour and environment, that is, context-awareness. Dynamic changes, for example, mood, must be detected and updated to provide personalized recommendations. Intelligence pursues dealing with uncertain environments where new knowledge must be discovered through approximation, reasoning or intuition.

Domain-specific analysis is recommended as an optimal computation strategy. Concerning new knowledge generation, data mining (DM) and artificial intelligence (AI) techniques are very recurrent.<sup>106</sup> AI is involved with the intelligence of the CDSS while DM with both intelligence and dynamism.

An additional feature could be the inclusion of visual analytics (VA). VA has the advantage of providing simple data and/or pattern views, as well as supporting visually decision-making activities.<sup>107</sup>

### *Ecological momentary assessment and intervention*

They offer the capability to monitor variations in user's everyday life and deliver behavioural responses in the appropriate context. EMA methods involve collecting real-time data, on repeated occasions and in context of daily life.<sup>108</sup> EMIs refer to delivering interventions for coping with everyday lives in real time and in the real world.<sup>109</sup>

These techniques are *ecologically* valid because they are based on the real-world environment (RWE). EMA captures data directly from the RWE, through automatic approaches or manual self-report. EMI delivers interventions in the most appropriate moment of the subject's everyday life.<sup>110</sup> Data capture via EMA runs parallel to the use of EMI.<sup>109</sup> *Momentary* indicates they are both focused on the user's current situation.<sup>110</sup> In 2010, Heron and Smyth<sup>109</sup> stated that real-time assessment and intervention proceedings were considered separately. Nowadays, the combo of EMA and EMI has become an important research area. First, EMA's results can inform and tailor the content and timing of EMI delivery, to be the most appropriate.<sup>109</sup> Heron and Smyth<sup>109</sup> states the importance of interventions with a certain level of tailoring. Second, EMA can trigger EMI if problematic data information is detected.<sup>109</sup> This helps addressing behavioural guidance, for example, self-care activities' delivery or instructions for medication adherence, or other interventions, for example, relaxation stimuli, when most needed.<sup>109</sup>

EMA and EMI implementation imply facing three main limitations<sup>110</sup>: (1) defining the set of questions to capture information data, (2) decide in which context to deliver the questions and (3) managing the EMI strategy.

### *Behaviour change theories and models*

The strategy to change a person's lifestyle consists on the application of evidence-based BCTs and BCMs. BCTs attempt to explain why behaviour changes by extracting the impact factors. BCMs address the behaviour change processes, so they allow predicting behaviours.

de Vries<sup>111</sup> referenced Lim and Dey<sup>112</sup> book, where they stated that 1700 constructs were used in 83 theories. de Vries<sup>111</sup> highlighted some famous health behaviour theories and models, such as health belief model (HBM),<sup>113</sup> social cognitive theory (SCT),<sup>114</sup> the theory of planned behaviour (TPB)<sup>115</sup> and the transtheoretical model (TTM).<sup>116</sup>

Integration of behavioural theories can be seen as an advantage by some people, such as reinforcing a theory by overcoming its weak points and by adding new elements.<sup>111</sup> In integration, unlike in combination, elements can only be added if they offer a supplementary theoretical and empirical value and if their addition will lead to develop and test new hypotheses. de Vries<sup>111</sup> presented an interesting health behaviour theory integration approach named integration-change model, where all of the previous theories – HBM, SCT, TPB and TTM – are integrated.

BCT Taxonomy v1 (BCTTv1)<sup>117</sup> might be helpful for implementation. This is a cross-domain, hierarchically structured taxonomy of 93 distinct BCTs with labels, definitions and examples.

## *Clinical guidelines*

Clinical guidelines state the action programmes in clinical practice.

Only 1 out of 19 VCSs indicated using clinical guidelines.<sup>72</sup> The VCS was about educating powered wheelchair users about the usage of seating functions, including prescribed personalized seating regimens.

Due to the lack of information about clinical guidelines in the VCS-related articles, Supplemental Table 8 proposes more implementable guidelines from different clinical knowledge domains: pharmacology, multiple comorbid diseases, diabetes mellitus, depression and falls.

## **Validation**

This section and Supplemental Table 9 review the relevant key factors involved in validation. It includes information related to subject population – number of sample and demographic data – and validation methodologies including the use of control groups.

Four out of nineteen articles did not include information about validation.<sup>118–121</sup> These are excluded from Supplemental Table 9.

### *Subject population*

Studies' subject population number varies considerably from 2 to 70. Blanson Henkemans et al.<sup>122</sup> had 118 participants but only 35 completed the whole process. Kyriazakos et al.<sup>123</sup> did not indicate the number of participants, but only said that next study would be larger up to 200. So, without considering,<sup>123</sup> the average number of subjects is 32. Differences could be justified by the validation methodology followed. For instance, Wu et al.<sup>72</sup> evaluated VCS's usability with five participants. According to a study, 80 per cent of usability problems can be detected by the first four or five subjects.<sup>124</sup>

General information about participants, for example, gender, age, ethnicity, education and so on, was extracted by demographic questionnaires in previous studies.<sup>125–127</sup> The sample of responders might not be an accurate representation of the population to address.

### *Validation methodologies*

Only a few validation protocols included control groups.<sup>125,128–131</sup> The rest of the studies analysed participants' progression to evaluate the VCS.

Among validation methodologies, questionnaires are the most frequent approach – 12 out of 19. Some studies may have used more than one.<sup>123,126,132,133</sup> Questionnaires can be grouped by whether they assess the VCS itself (Sullivan and Artino<sup>134</sup> in Asselin et al.,<sup>135</sup> Laugwitz et al.<sup>136</sup> and Davis<sup>137</sup> in Kyriazakos et al.<sup>123</sup>), participants' progress (Harris and D'Eon,<sup>138</sup> Cleeland and Ryan<sup>139</sup> and Hoehn and Yahr<sup>140</sup> for Parkinson in Ellis et al.,<sup>132</sup> Folstein et al.<sup>141</sup> in French et al.<sup>119</sup> and Kyriazakos et al.<sup>123</sup> and Thomas et al.<sup>142</sup> in Bickmore and Brown<sup>126</sup> and Lins and Carvalho<sup>143</sup> in Kyriazakos et al.<sup>123</sup>) and participants' subjective data (Horvath and Greenbargh<sup>144</sup> in Bickmore and Brown<sup>126</sup> and Lessiter et al.<sup>145</sup> in IJsselsteijn et al.<sup>133</sup>).

Alternative approaches to questionnaires included interviews<sup>123,146</sup> and self-reported data usage<sup>130,122,129</sup> methods. There were also some objective data-gathering methods for validation. Objective data was used for physical capacity evaluation in Kyriazakos et al.<sup>123</sup> and Buttussi et al.<sup>127</sup>

The wide variety of validation methodologies states that there is eventually not a standard validation protocol. Validation methods were designed for determined VCSs. Another open issue in validation could be related to the independent contribution of the self-monitoring approach and the VCS.

## Discussion

Nowadays, there is a paucity of literature concerning VCSs – 19 articles, especially for older adults – 5 articles. However, an increase is expected in the coming years, thanks to the European H2020 programme<sup>147</sup> and the funded projects.<sup>148–153</sup>

The lack of a common design space could lead to misunderstandings between researchers. This article proposes a literature-based design space and defines a structured VCS framework, to provide common guidelines for posterior publications about this topic.

In order to situate researchers in the current state of VCSs, a state-of-the-art is provided. Information about the VCS components was extracted and presented in review tables. However, articles excluded for not fulfilling the definition used in this survey are referred to in the core of the section. In addition, validation approaches are analysed.

Future work involves testing the applicability and extrapolation of the proposed design space in future VCSs<sup>148–154</sup> and surveillance of their progress and discoveries. Main challenges include the definition of methodologies to select the right method to develop each design space component and interconnect them adequately.

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## Supplemental material

Supplemental material for this article is available online.

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