Gaze direction affects walking speed when using a self-paced treadmill with a virtual reality environment

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ABSTRACT

Background: In a previous study it was observed that participants increase their walking speed during a dual task while walking on a self-paced treadmill in a virtual reality (VR) environment (Gait Real time Analysis Interactive Lab (GRAIL)). This observation is in contrast with the limited resources hypothesis, which suggests walking speed of healthy persons to decrease when performing a cognitive dual task.
Aim: The aim of the present study was therefore to determine whether the cognitive demand of the task, an aroused feeling, discrepancy in optic flow or a change in gaze direction caused participants to walk faster in this computer assisted rehabilitation environment.
Materials: The GRAIL included a self-paced treadmill, a motion-capture system and synchronized VR environments.
Methods: Thirteen healthy young adults (mean age 21.6 ± 2.5) were included in this study. Participants walked on the self-paced treadmill while seven different intervention conditions (IC) were offered. Prior to each IC, a control condition (CC) was used to determine the natural self-selected walking speed. Walking speed during the last 30 s of each IC was compared with the walking speed during the last 30 s of the preceding CC.
Results: Results show that the height on which a visual task was presented in the VR environment, influenced walking speed. Participants walked faster when gaze was directed above the focus of expansion.
*Significance:* These findings contribute to a further understanding of the differences between walking in a real life environment or computer assisted rehabilitation environment. When analyzing gait on a self-paced treadmill in the future, one must be attentive where to place a visual stimulus in the VR environment.

1. Introduction

Overground walking speed of healthy persons decreases when performing a cognitive dual task (Al-Yahya et al., 2011). This phenomenon can be explained by the limited resources hypothesis, which states that humans are limited in the amount of attention they are able to give to multiple tasks (Wickens, 1991). Humans redirect their attention towards cognitive-task performance and away from gait performance, causing a decrease in walking speed (Wrightson, Ross, & Smeeton, 2016). This occurs for instance when performing the color-word Stroop task (Patel, Lamar, & Bhatt, 2014). For this reason, it is expected that participants also decrease their walking speed when performing a color-word Stroop task, using the Gait Real-time analysis Interactive Lab ((GRAIL), MotekForce Link Amsterdam BV, The Netherlands), which aims to represent the real world (Motek Medical, 2013). The GRAIL is a computer assisted rehabilitation environment (van der Meer, 2014) and includes a self-paced treadmill, a motion-capture system and synchronized virtual reality (VR) environments (Motek Medical, 2013).

However, in previous research (Oude Lansink, van Kouwenhove, Dijkstra, Postema, & Hijmans, 2017) it was observed, during an additional measurement, that participants did not decrease, but instead increase their walking speed during a dual task (please find

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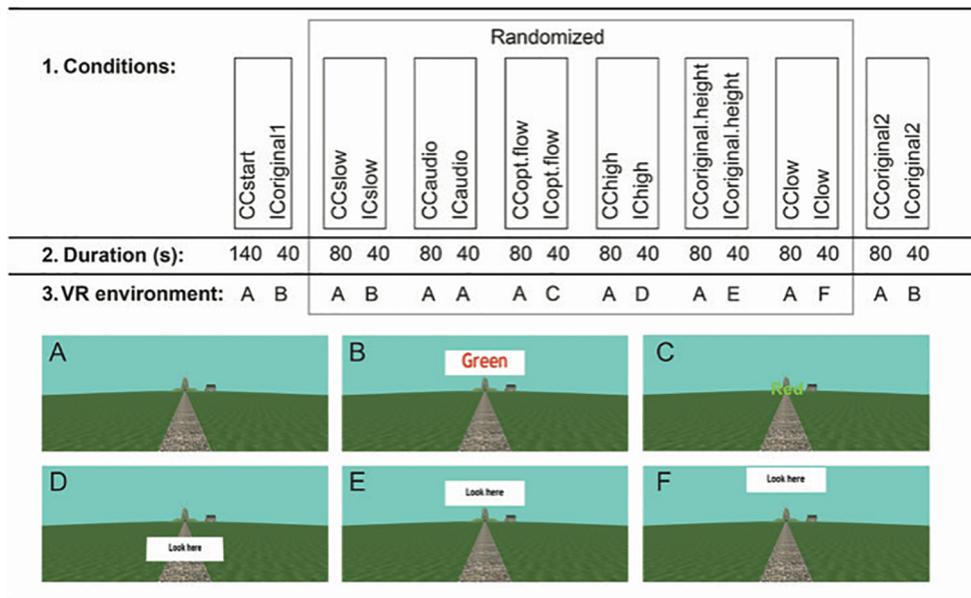
Fig. 1. Study design. **1.** Schematic overview of the conditions from left to right. Each block represents an IC with its corresponding CC and these IC and CC are always presented right after each other. The middle six blocks were randomized for each participant; **2.** The duration of the above CC/IC in seconds; **3.** The VR environment that was presented during the above CC/ IC. Screenshots of the VR environment are indicated with the letters A through F. Screenshots include the translated text from Dutch to English.

these data in Appendix 1). To clarify why participants increased their walking speed, three aspects, other than the cognitive demand of the Stroop task, need to be reviewed.

First, participants could have felt aroused while performing the color-word Stroop task. A Stroop task word switched to the next Stroop task word, after being presented for 1.5 s. This gave participants a limited amount of time to call out the color of the word, which could have caused a state of arousal. It has already been shown that arousing stimuli can cause an increase in walking speed (Leman et al., 2013). Listening to active music caused participants to walk faster than when listening to relaxed music, despite all music having a tempo of 130 beats per minute (Leman et al., 2013).

Second, participants experienced discrepancy in optic flow while performing the color-word Stroop task. To be more specific, the Stroop task was presented on a large, white pane (0.53 × 1.53 m), which covered part of the optic flow (Fig. 1B). Previous research showed that participants decrease their walking speed in the presence of artificial optic flow (a VR environment) (Fink, Foo, & Warren, 2007; Mohler, Campos, Weyel, & Bülthoff, 2007). Blocking (part of) the artificial optic flow might therefore increase walking speed again. This was indeed shown in a previous study (Baumberger, Fluckiger, & Martin, 2000), where participants increased their walking speed when the approaching artificial optic flow was stopped. Therefore, the discrepancy in the VR environmental optic flow, due to the white pane of the Stroop task, potentially caused participants to walk faster.

Third, participants might have redirected their gaze from just under or at the focus of expansion, towards the white pane that was projected higher. It has been shown (Patla & Vickers, 1997; Turano, Geruschat, Baker, Stahl, & Shapiro, 2001) that participants, while walking a simple route, directed 75% of their gaze ahead on the path, nearby the focus of expansion or at an end goal. Participants monitored the rest of their environment with their peripheral vision (Turano et al., 2001). Only in the presence of obstacles, participants redirect their gaze away from the focus of expansion (Patla & Vickers, 1997). Therefore, it is expected that participants in the previous study (Oude Lansink et al., 2017) also fixed their gaze mainly on the path, nearby the focus of expansion or at the windmill (the path's end goal), before performing the Stroop task. Since the Stroop task was presented above the focus of expansion, participants had to redirect their gaze and fix it higher. To our knowledge, no studies have examined the effect of gaze direction on walking speed while walking on a self-paced treadmill in a VR environment.

The aim of the present study is to verify the increased speed and to determine why participants increased their walking speed when performing a color-word Stroop task, while walking on a self-paced treadmill in a VR environment. It is hypothesized that the cognitive demand of the Stroop task, an aroused feeling among participants, discrepancy in optic flow or a change in gaze direction caused participants to walk faster.

2. Methods

2.1. Participants

Fourteen healthy volunteers participated in this study. Participants needed to be naïve to the purpose of the study and have no

Table 1

Self-reported baseline characteristics of the 13 included participants (92.3% female).

	Mean ± SD
Age (y)	21.6 ± 2.5
Weight (kg)	68.5 ± 6.8
Height (m)	1.74 ± 0.05

self-reported physical problems that could influence their walking pattern. One participant expected walking speed to be examined and was therefore not naïve to the purpose of study and excluded. Baseline characteristics of the included participants are shown in Table 1. All participants signed a written informed consent form. The study was approved by the local Medical Ethics Committee (2017/188).

2.2. Materials

The present study used the same self-paced treadmill and algorithm as was used in the previous study (Oude Lansink et al., 2017), with a VR environment projected on the treadmill and on a 180° semi-cylindrical screen (GRAIL, MotekForceLink Amsterdam BV, The Netherlands). The VR environment involved a straight, endless path towards a windmill and house (Fig. 1A). Optic flow, in the form of approaching grass and path stones, was constantly synchronized with the treadmill speed via a self-paced speed algorithm. As explained by Sloot, van der Krogt, and Harlaar (2014), the self-paced algorithm corrects the speed of the treadmill belt proportional to the difference in position between the participant and the middle of the belt. In other words, when participants drift backward, treadmill speed decreases and when participants drift forward, treadmill speed increases. Four markers on the pelvis were used to determine the pelvis position and walking speed of participants via an integrated motion capture system (VICON Bonita 10, Oxford, UK). D-Flow software (version 3.28) was used to integrate and synchronize all components (MotekForceLink Amsterdam BV, The Netherlands). The exact operation of the D-flow software is explained by Geijtenbeek and Steenbrink (2011).

2.3. Study design

Participants walked on the treadmill, while seven different intervention conditions (IC) were offered. These involved the original Stroop task (ICoriginal) as performed in the previous study (Oude Lansink et al., 2017), a slower version of ICoriginal (ICslow), ICoriginal where optic flow was still present (ICopt.flow), an audio Stroop task (ICaudio) and a pane at three different heights, directing the gaze of the participants low in the VR environment (IClow), at the original Stroop task height (ICorig.height) and higher (IChigh). Each IC was offered for 40 s. ICoriginal was always offered at the start and end of each trial, but the order of all other IC was randomized for each participant. This way, learning effects or effects caused by fatigue or a decline in concentration, could be eliminated. Furthermore, a control condition (CC) was always offered before an IC to first reset the walking speed and then determine the self-selected walking speed at that moment. CC was offered once for 120 s and all other times for 80 s. Taken all IC and CC together, participants walked a total of 17 min on the treadmill. All tasks were presented in Dutch. A schematic overview of the study design is shown in Fig. 1. Additional information about the conditions can be found under the section 'Experimental conditions'. Finally, after a trial, participants were asked where in the VR environment they mainly directed their gaze during CC.

2.4. Experimental conditions

CC: During the first part of CC, treadmill speed was fixed at 1 m/s for 20 s. During the second part of CC, participants could determine their own walking speed, due to the self-paced mode of the treadmill. The self-paced mode lasted 2 min the first time CC was presented (CCstart) and 1 min all the other times. A pre-set audio voice was played, saying "Start walking" at the start of CCstart, "The treadmill will now proceed on a fixed speed" at the start of all other CC's and "Now, walk on a pace that is comfortable for you" when the fixed-speed mode ended and the self-paced mode began.

ICoriginal1 and ICoriginal2: The aim of ICoriginal was to determine whether participants indeed walked faster on the self-paced treadmill while performing the color-word Stroop task. This way a within-participant design could be used. The Stroop task was presented on a white pane (0.52 × 1.53 m), which caused some discrepancy in optic flow (Fig. 1B). The height of the pane was 1.55 m, measured from treadmill level till the bottom side of the pane. The interval between the Stroop task words was 1.5 s and the color-word Stroop task began after a pre-set audio voice was played, saying 'Name the color of the written word'.

ICaudio: At the start of ICaudio, a pre-set audio voice was played, saying 'Tell whether the word is said on a high tone or a low tone'. Thereafter, another pre-set audio voice called on the words 'high' and 'low' randomly with an interval of 1.5 s. The words were offered on a high or low voice pitch, which was again randomly assigned. This created two situations, one where a word did match the pitch and one where the word did not match the pitch. Especially the no-match situations ask for a higher cognitive demand (McClain, 1983).

ICslow: The experimental set-up of ICslow was equal to ICoriginal, except that the interval between words was extended to 3 s, so the hypothesis is that the participants were less aroused.

Table 2
An overview of outcomes that would fit the four hypothesized speed increasing causes.

	Did participants walk significantly faster during IC compared to the corresponding CC?							
	ICoriginal1	ICslow	ICaudio	ICopt.flow	IChigh	ICorig.height	IClow	ICoriginal2
Hypothesized causes[a]:								
1. Cognitive demand	Yes	Yes	Yes	Yes				Yes
2. An aroused feeling	Yes		Yes	Yes				Yes
3. Discrepancy in optic flow	Yes	Yes			Yes	Yes	Yes	Yes
4. Change gaze direction								
a. Higher gaze direction	Yes	Yes			Yes	Yes		Yes
b. Gaze direction at the original Stroop task height	Yes	Yes				Yes		Yes

Note: 'Yes' indicates a significant difference between the IC and its preceding CC.

[a] It is hypothesized that the cognitive demand of the Stroop task (1), an aroused feeling among participants (2), discrepancy in optic flow (3) or a change in gaze direction (4) caused participants to walk faster.

ICopt.flow: The experimental set-up was equal to ICoriginal, except that the Stroop task's words were not presented on a white pane. Instead, the words were placed in the VR environment where they moved along with the optic flow (Fig. 1C). The color word started at the focus of expansion and moved towards the person, resulting in a decrease in height and increase in size of the word over the 1.5 s presentation. This way, optic flow was fully present.

IClow, ICorig.height and IChigh: The white pane (0.52 × 1.53 m), on which the original color-word Stroop task was presented, was now presented at three different heights: IChigh = 1.80 m, ICorig.height = 1.55 m and IClow = 0.25 m (all measurements represent the distance between the treadmill height and the bottom side of the white pane). Only the text 'Look here' was written in Dutch on the further empty, white pane (Fig. 1D–F). This way discrepancy in optic flow was created, combined with offering three different gaze directions.

2.5. Data analysis

Participant's walking speed was calculated by adding the velocity of the pelvis in ventral-dorsal direction to the treadmill speed. All calculations were done using MATLAB (Version R2017a for Windows, The Mathworks Inc. Natick, UN). Only the last 30 s of each CC and IC were taken for further analysis, as walking speed was relatively constant in that interval.

Statistical analysis was performed using IBM SPSS statistics software (Version 24.0 for Windows, SPSS Inc. NY, USA). Multiple paired sample *t*-tests were used to analyze which IC differed significantly from its preceding CC. Considering the 6 different IC and ICoriginal1 and ICoriginal2 as verification of previous findings, a Bonferroni correction for (6) multiple comparisons was applied, resulting in an adjusted alpha of 0.008 (0.05/6). Table 2 shows the combinations of outcomes that would be in agreement with the hypotheses.

3. Results

All participants (n = 13) successfully completed the experiment. Results of the multiple paired sample *t*-tests show that walking speed during ICoriginal1 (t(12) = −4.58, p = 0.001), ICslow (t(12) = −6.28, p = < 0.001), ICorig.height (t(12) = −3.72,

Table 3
Comparison of the mean walking speed during the last 30 s of each IC compared to the last 30 s of the preceding CC.

	Mean walking speed (m/s) ± SD		Difference (%)	t[a] (df)	p-value	d[b]
	CC	IC				
ICoriginal1	1.14 ± 0.22	1.30 ± 0.27	14.0	−4.58 (12)	0.001[*]	0.65
ICslow	1.30 ± 0.18	1.45 ± 0.17	11.5	−6.28 (12)	< 0.001[*]	0.89
ICaudio	1.28 ± 0.19	1.36 ± 0.25	6.3	−1.64 (12)	0.127	0.37
ICopt.flow	1.27 ± 0.15	1.28 ± 0.25	0.8	−0.16 (12)	0.879	0.05
IChigh	1.24 ± 0.18	1.30 ± 0.18	4.8	−2.86 (12)	0.014	0.30
ICorig.height	1.26 ± 0.12	1.36 ± 0.09	8.7	−3.72 (12)	0.003[*]	0.97
IClow	1.27 ± 0.14	1.31 ± 0.15	3.1	−1.36 (12)	0.198	0.24
ICoriginal2	1.32 ± 0.13	1.47 ± 0.15	11.4	−3.55 (12)	0.004[*]	1.09

[a] Paired sample *t*-test (two tailed).
[b] Effect size using Cohens d.
[*] Significance p ≤ 0.008.

Table 4

An overview of the actual study outcomes and outcomes that would fit the four hypothesized speed increasing causes. As indicated with a red box, only the hypothesized outcomes of a change in gaze direction causing participants to walk faster (4), are in agreement with the actual study outcomes.

	Did participants walk significantly faster during IC compared to the corresponding CC?							
	ICoriginal1	ICslow	ICaudio	ICopt.flow	IChigh	ICorig.height	IClow	ICoriginal2
Actual study outcomes	**Yes**	**Yes**				**Yes**		**Yes**
Hypothesized causes[a]:								
1. Cognitive demand	**Yes**	**Yes**	Yes	Yes				**Yes**
2. An aroused feeling	**Yes**		Yes	Yes				**Yes**
3. Discrepancy in optic flow	**Yes**	**Yes**			Yes	Yes	Yes	**Yes**
4. Change gaze direction								
c. Higher gaze direction	**Yes**	**Yes**			Yes	Yes		**Yes**
d. Gaze direction at the original Stroop task height	**Yes**	**Yes**				**Yes**		**Yes**

Note: 'Yes' indicates a significant difference between the IC and its preceding CC. Bold indicates the outcomes that are in agreement with the actual study outcomes.

[a]It is hypothesized that the cognitive demand of the Stroop task (1), an aroused feeling among participants (2), discrepancy in optic flow (3) or a change in gaze direction (4) caused participants to walk faster.

p = 0.003) and ICoriginal2 (t(12) = −3.55p = 0.004) was significantly larger compared to their preceding CC (Table 3). The other interventions showed no significant difference in walking speed between IC and CC.

Furthermore, a time-effect is present when comparing CCstart with CCoriginal2 (t = −3.51 (13), p = 0.004) and ICoriginal1 with ICoriginal2 (t = −2.17(13), p = 0.050).

4. Discussion

The aim of the present study was to determine whether the cognitive demand of the Stroop task, an aroused feeling, discrepancy in optic flow or a change in gaze direction caused participants to walk faster when performing a color-word Stroop task on a self-paced treadmill in a VR environment. The results show a significant increase in walking speed when performing ICoriginal, ICslow and ICorig.height. Where gaze was directed between 1.55 m and 2.07 m above the treadmill height, on eye level or just above. Therefore, it can be concluded that the change in gaze direction caused participants to walk faster (Table 4).

It appeared that at the start of the experiment, participants had to get used to the GRAIL, since mean walking speed was only 1.14 m/s during the first control condition (CCstart). This was found to be significant lower than the mean walking speed during the last control condition (CCoriginal2), where it was increased to 1.32 m/s. This finding is in line with previous research using a self-paced treadmill and VR environment, where participants also walked faster at the end of the experiment as opposed to the start of the experiment (Souman et al., 2011). They showed that mainly step length was shorter during the first trials, but increased over the course of the trials (Souman et al., 2011). This indicates that participants need time to get fully comfortable with the self-paced algorithm and VR environment.

A significant increase in walking speed was found in all interventions where participants had to look between 1.55 m and 2.07 m above the treadmill height (Fig. 1B and E). A trend towards faster walking speed was observed in the IChigh condition (p = 0.014). Based on this outcome we cannot state whether the high gaze direction results in faster walking speed or not. It remains uncertain why a change in gaze direction causes participants to walk faster. However, a possible explanation could be that there is no point of reference visible for participants to determine their position on the treadmill when gaze is directed on eye level or just above. When points of reference, such as the treadmill, the ground of the real world environment, the edges of the VR screen or the ceiling are completely out of (peripheral) sight, participants might feel more safe at the front part of the treadmill to ensure they will not fall off the treadmill. Therefore, it is hypothesized that participants (unintentionally) move forward to ensure that they will not fall off the treadmill. Due to the self-paced speed algorithm (Sloot et al., 2014), moving forward results in an increase of the treadmill speed and therefore walking speed. This way, walking speed might continue to increase, until participants reach a certain walking speed that does not feel safe to carry out anymore. None of the participants reached the maximum treadmill speed (2 m/s). The focus of

participants could then switch to stabilizing the current walking speed, still resulting in an overall higher walking speed during IC compared to CC. However future research is needed to examine this hypothesis.

Another explanation could be that participants walked slower than their normal walking speed during CC and returned to this normal waking speed when no point of reference was visible during IC. Previous research found that participants walk slower than their overground walking speed, when walking on a self-paced treadmill in a VR environment (Souman et al., 2011) or when only using the VR environment (Fink et al., 2007; Mohler et al., 2007) or self-paced treadmill (Dasilva et al., 2011; Fellin, Seay, Gregorczyk, & Hasselquist, 2016; Vogt, Pfeifer, & Banzer, 2002; Yang & King, 2016). Although the present study did not measure participant's overground walking speed, walking speed during ICoriginal, ICslow and ICorig.height was indeed close to the mean overground walking speed of men (1.36 m/s) and women (1.34 m/s) aged 20–29 years, found in a previous meta-analysis for normal walking speed (Bohannon & Williams Andrews, 2011). This could suggest that participants walked closer to their normal walking speed when no point of reference was visible or when being distracted. However, mean walking speed of CCslow (1.30 ± 0.18 m/s) and CCoriginal2 (1.32 ± 0.13 m/s) approach normal overground walking speed more than respectively ICslow (1.45 ± 0.17 m/s) and ICoriginal2 (1.47 ± 0.15 m/s). Furthermore, mean walking speed of ICaudio (1.36 ± 0.25 m/s), ICopt.flow (1.28 ± 0.25 m/s) and IClow (1.31 ± 0.15 m/s) approach the assumed normal walking speed, but do not differ significantly from respectively CCaudio (1.28 ± 0.19 m/s), CCopt.flow (1.27 ± 0.15 m/s) and CClow (1.27 ± 0.14 m/s). These findings indicate that participants did not walk structurally slower than the assumed normal walking speed during CC. Still, they walked structurally faster than CC during the interventions where gaze was directed on eye level or just above. Therefore, this explanation is less probable.

A limitation of the present study is that the overground walking speed was not measured. Measuring the overground walking speed would have given more insight in how the interventions and the self-paced treadmill, influence the natural walking speed. Therefore, it is advised to include the overground walking speed in future research on gait parameters, when using a self-paced treadmill or VR environment.

Another limitation is that the present study did not allow to measure gaze direction with eye tracking and could therefore not determine exactly where participants gaze was directed during CC. However, this does not influence the conclusion that participants by all means walked faster when asked to direct their gaze on eye level or just above. Still, it would be interesting for future research to further investigate the overall 'natural' gaze height when using the GRAIL, so that visual stimuli can be offered at this height to limit walking speed differences as much as possible when needed.

Last, the present study did not use a fully balanced design. Our hypotheses rely on significant differences between some of the intervention conditions and the control conditions while others comparisons should be equal. Only differences were tested. When no differences were found we considered control and intervention conditions to be equal. A limitation of this study is that we did not perform equivalence testing. Although this could have strengthened our claims in this study it requires a very large sample size. Considering the early (pilot) stage of this study we decided not to incorporate this in the study design.

An important strength of the present study is that it calls attention to the dependency of participant's walking speed on their gaze direction in a computer assisted rehabilitation environment, using a self-paced treadmill and VR environment. So far, no study examined the effect of gaze direction on walking speed using a self-paced treadmill an VR environment. Therefore, the present study contributes to a further understanding of the differences between walking in a real life environment or a computer assisted rehabilitation environment.

5. Conclusion

The present study showed that the height of a visual task in a VR environment, influences walking speed when walking on a self-paced treadmill. Participants walked faster when gaze was directed on eye level or just above. The study underlines the existence of discrepancies between using a computer assisted rehabilitation environment or real life environment. When analyzing gait on a self-paced treadmill, one must be attentive where to place a visual stimulus in the VR environment.

Future research is needed to determine why gaze directed on eye level or just above causes participants to walk faster when walking on a self-paced treadmill in a VR environment.
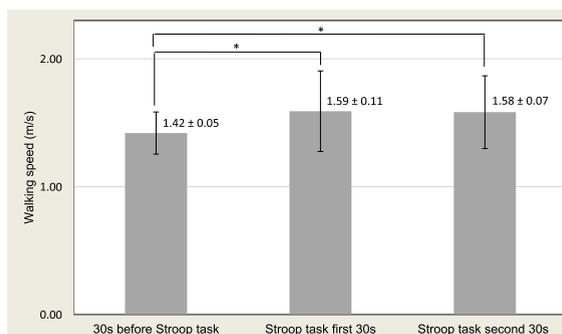
Declarations of Competing Interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix 1

See Fig. A1.

Fig. A1. Unpublished observation of previous research (Oude Lansink et al., 2017) during an additional measurement of walking speed on the GRAIL with and without a Stroop task. The figure shows 90 s of participants walking speed (mean ± SD) on the GRAIL. 0–30 s; control measurement – no additional task was presented|30–90 s; a Stroop task was presented (N = 28). *p < 0.001 after comparison using a paired sample *t*-test.

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