An investigation of the effect of immersive visual and auditory feedback on rhythmic walking interaction

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ABSTRACT

We present a study whose goal is to investigate the role of immersive visual and auditory feedback to affect preferred walking pace and perceived ease and naturalness of walking actions. Additionally, we measured how the congruence between visual and auditory stimuli affects perceived ease of walking. The visual feedback was presented through a head mounted display and auditory feedback was delivered based on the detected footsteps of participants. Subjects were asked to walk in place on top of an aerobic stepper at the pace they preferred. Their tempo was detected while walking. After each trial the participants answered a series of questions. Results of the experiment show that different footstep sounds affect walking pace, visual feedback, however, did not influence the chosen walking pace. The questionnaire data indicate that perceived congruency between visuals and footstep sounds correlate with the rating of the ease of walking (the more congruent variables, the easier to walk for participants).

CCS Concepts

•Human Computer Interaction → HCI design and evaluation methods; Empirical studies in HCI;

Keywords

auditory feedback, immersive visual feedback, rhythmic interaction

1. INTRODUCTION

Walking is an activity that has received lots of attention in recent years in the sonic interaction design as well as in the virtual reality community. In the sonic interaction design community, research has mostly investigated how to simulate natural walking feedback using physics based algorithms [5]. In the virtual reality community, research has spanned through different directions; examples are interfaces to control walking experiences [2, 14], the creation of infinite walking in a finite laboratory [23, 27], as well as perceptual evaluations of several parameters related to walking [1, 25]. A relatively recent overview of different research directions related to walking in virtual reality can be found here [26].

In previous research, we studied walking as a rhythmic action and experimentally investigated the effect of auditory feedback on this action, within the framework of closed-loop interactive sonification [9]. We were particularly interested in observing whether different auditory cues would affect peoples' gait at different tempi. As the input modality tracking the footsteps we have utilized audio, captured near the feet with contact microphones [11, 12, 13]. Our aim was to study how different rhythmic cues affect the walking rhythm, thus providing insight into the design of rhythmic feet-based interactive systems. We especially considered different temporal forms of the feedback; namely, direct synthetic response to each step, and both natural and unnatural continuous synthetic audio feedback with and without tempo adaptation to the human gait.

Our previous studies were all devoid of visual feedback. However, previous work has suggested that visual stimuli may also influence how individuals walk. Particularly, it has been documented that optic flow may be influential. Work by Pailhous et al. [20] suggests that individuals reduce their walking speed in response to floor-projections of patterns of dots moving backwards, and Konczak [10] found that individuals will increase or decrease their walking speeds in response to forward or backward displacement of the walls of a physical corridor. Studies by Warren et al. [28] and Prokop et al. [22] required participants to walk on a treadmill while watching a optic flow patterns displayed on wide-FOV projection screens. Their results suggests that decreased rates of expansion or contracting optic flow fields led to increases in walking speeds, wheras increased rates of expansion led to decreases in walking speed. Mohler et al. [15] described work demonstrating that visual motion cues may influence gait transition speeds and preferred walking speeds. Particularly, the participants were walking on a treadmill and visually projected speeds were either slower than, identical to, or faster than the actual walking velocity. The results suggested that higher visual speeds led to lower gait transition speeds and lower preferred walking speeds. These studies indicate that gait properties may be influenced by varying the visual motion cues indicative of self-motion. However,

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some work has also suggested that the content of the visuals themselves might also influence the behaviour of the walker. Particularly, Franěk et al. [6, 7] reported that the amount of greenery and traffic, along with factors such as noise, may influence how fast individuals tend to walk. Notably this work was performed in real-life settings.

Interestingly, one of our previous studies [11], yielded somewhat similar indications; i.e., we found that the addition of soundscapes representing different contexts may influence the preferred pace of users who are walking in place. Particularly, when soundscapes and footstep sounds are congruent, previously observed effects of footstep sounds appear to become even more pronounced. Considering the seeing influence of visual stimulation, the aim of the current study is to twofold: (1) To explore if footstep sounds continues to have an effect in the presence of visuals. (2) To explore if audiovisual congruence similarly intensifies the effect of footstep sounds.

2. METHOD AND MATERIALS

In order to meet the aims described in the previous section, we performed a within-subjects study based on a 4×4 factorial design, crossing four different footstep sounds (wood, gravel, sinusoid, and no audio) and four different visual environments (wooden floor, gravel path, equivocal white surface, and no visuals). Thus, each participant was exposed to a total of 16 conditions.

2.1 Participants and procedure

A total of 20 participants (12 males, 8 females), aged between 19-40 years (M=26.7 years, SD=7.2), took part in the experiment. All participants reported having normal or corrected-to-normal hearing and vision. No compensation was offered for participation.

The participants performed a total of 16 walks (one for each condition) and were exposed to the conditions in randomized order. During each walk, the participants were asked to walk in place on an aerobic stepper in the pace they preferred. Particularly, they were walking in place on the stepper and did not step up and down from it. After each walk the participants answered a series of questions related to their experience of the presented feedback (see section 2.3).

2.2 Setup and stimuli

The participants' steps in place were performed on an aerobic stepper and detected using a Shure BETA 91 microphone placed underneath the stepper.

The auditory stimuli were generated using Max/MSP and played back using a pair of Sennheiser HD 600 circumaural headphones. The sounds of stepping on wood and gravel were produced using a physics-based sound synthesis algorithm driven by the amplitude envelope extracted using the microphone (for more details on the synthesis algorithm and step detection see [11, 13, 19]).

The visual stimulus was created in Unity 3D and delivered using a the Oculus Rift DK2 head-mounted display (HMD) that has a resolution of 960×1080 in each eye and 100° nominal field of view (FOV). This stimulus did as suggested comprise three different visual environments and no visuals feedback. It has been suggested that visually perceived differences in the environment may influence perception of speed [3], and people walking on a treadmill tend to change the walking speed in response to varying visual speeds [22, 28]. Thus, we aspired to keep visual cues producing optic flow constant, and the three environments therefore only differed in terms of the material used to represent the surface the participants were walking on; i.e., a wooden floor, a gravel patch and an equivocal white surface (Figure 1). The hope was that this would ensure that any observed effects were caused by different interpretations of ground material (top-down factor) rather than varying optic flow (bottom-up factor). The participants also wore the HMD during the condition with no visuals, but nothing was shown on the display. The orientation of the participants' heads were tracked using the intertial sensors embedded in HMD.

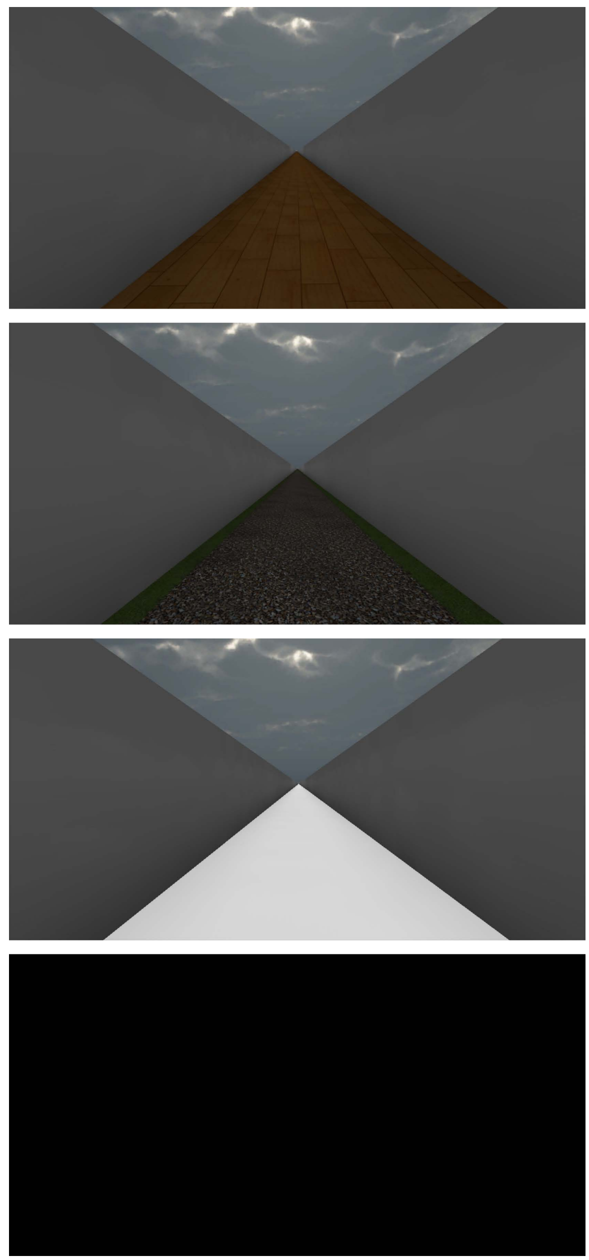

Figure 1: The four visual conditions used for the study. From the top: wooden floor, gravel path, equivocal white surface, and no visuals.

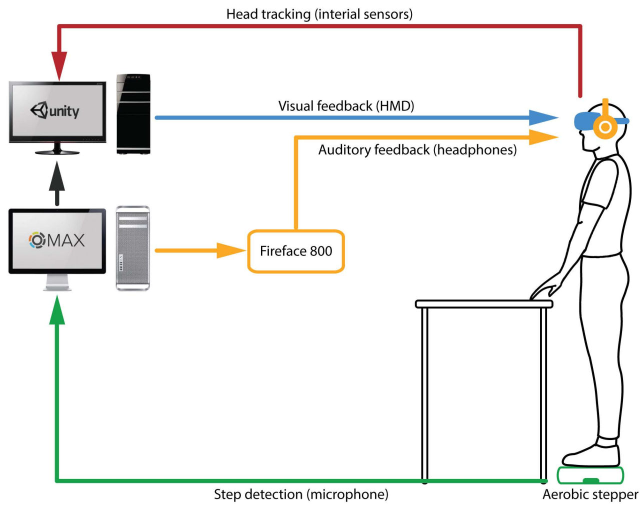

Figure 2: Schematic drawing of setup used for the study.

Walking in place is a well-established way of generating virtual movement in relation to virtual reality applications (see e.g., [4, 24, 29]). Thus, our approach to generating virtual motion was inspired by an existing technique that uses knowledge of human biomechanics to produce realistic walking speeds [29]. To be exact, walking velocity ($|v|$) can generally be expressed as the product of step frequency (f) and step length (l) [30], and since step length is correlated with height (h) it is possible to estimate the normal walking speed at a given step frequency from an individual's height:

$$|v| = (\frac{f}{0.157} \times \frac{h}{1.72})^2 \qquad (1)$$

where the constant 1.72 represents a common height and 0.157 is a constant (for details see [29]). The estimate of h was based on self-reports. The step frequency f was derived by averaging the step frequency obtained from the last 20 steps. This ensured that virtual movement remained smooth even if single steps were not detected. The smooth motion naturally came at the expense of the ability to make sudden changes to the velocity. However, this was not believed to be an issue since the participants were asked to walk at a constant pace. It has been documented that individuals walking in place through virtual environments tend to find realistic walking speeds to slow [18], making it necessary to apply a visual gain in order to ensure a natural walking experience. We applied a gain of 1.75 which has been found to produce natural motion perception in relation to displays with a similar FOV [18]. Since all conditions required the participants to walk along a straight line, no steering was implemented. Individuals walking in place while wearing a HMD tend to physically drift in the direction which they are headed within the virtual environment [16, 17]. Thus, in order to minimize positional drift and ensure the comfort and safety of the participants, they were required to hold on to a table during all walks. Figure 2 shows a schematic drawing of the setup.

2.3 Measures

A combination of behavioural and self-reported measures were used to gather data during the experiment.

In regards to the participants' behaviour, their step frequency was logged in order to provide an estimate of their preferred tempo. Particularly, during each walk the estimated tempo was derived from a moving average of six previous onset-to-onset interval values.

The participants' experience of each condition was assessed by means of a questionnaire administered after each walk. Most of the questionnaire items (Q1-Q7) required the participants to verbally rate their level of agreement with a given statement on Likert-type scales ranging from '1' to '7', and one item (Q7) asked the participant to identify the surface they had just been walking on.

Q1 Evaluate the sense of effort you experienced while walking ('1'=no effort, '7'=high effort).

Q2 It was easy to walk while listening to the sounds of footsteps and watching the visuals ('1' = very easy, '7' = very hard).

Q3 The pace I kept while walking was ('1' = very slow, '7' = very fast).

Q4 Feedback felt as a natural consequence of walking. Consider only footsteps sounds ('1' = strongly disagree, '7' = strongly agree).

Q5 Feedback felt as a natural consequence of walking. Consider footsteps sounds and visuals ('1' = strongly disagree, '7' = strongly agree).

Q6 Feedback was congruent with visuals ('1' = strongly disagree, '7' = strongly agree).

Q7 What type of surface you have been walking on (open-ended question)?

Note that Q1 and Q3, were presented after all conditions, Q2 - after all conditions without the last one (no feedback and no visuals). Q4 was only presented after exposure to conditions involving auditory feedback, and Q5 and Q6 were only used after audiovisual conditions. Q7 was only presented when either auditory or visual feedback was presented.

3. RESULTS

In this section we summarize the results pertaining to the participants preferred tempo and results of the self-reports collected after each trial.

3.1 Preferred Tempo

The mean tempo across each trial was used as an estimate of the participants preferred tempo during exposure to the individual combinations of feedback (Figure 3). Comparison by means of factorial repeated-measures ANOVA revealed a significant main effect of footsteps sounds variable on the preferred tempo ($F(1.89, 35.98)=2.75$, $p<0.05$). As in our previous studies [11, 12, 13], the sound of gravel motivated the participants to walk in the slowest pace, then the sound of wood and the sine wave. The participants walked the fastest when no additional auditory feedback was presented. No significant effect of visual feedback was found.

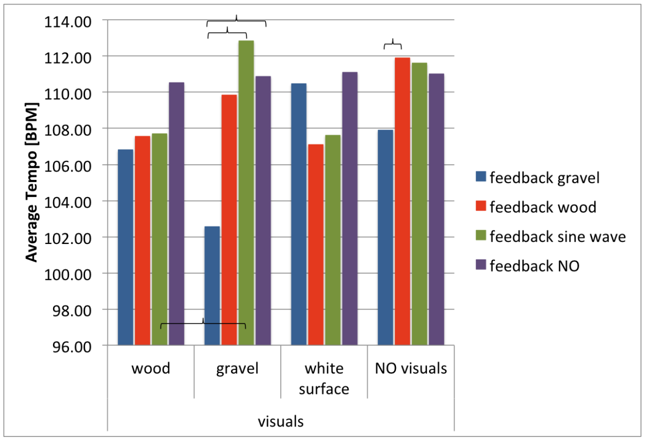

Figure 3: A visualisation of the experiment results for average tempo. The horizontal brackets present significant differences between conditions (p<0.05).

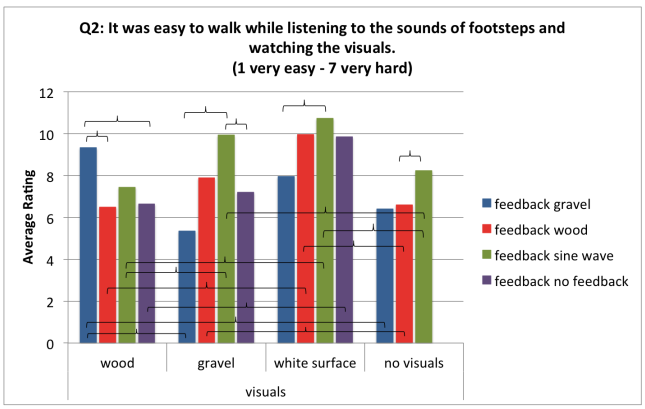

Figure 4: A visualisation of the experiment results for the Q2. The horizontal brackets present significant differences between conditions (p<0.05).

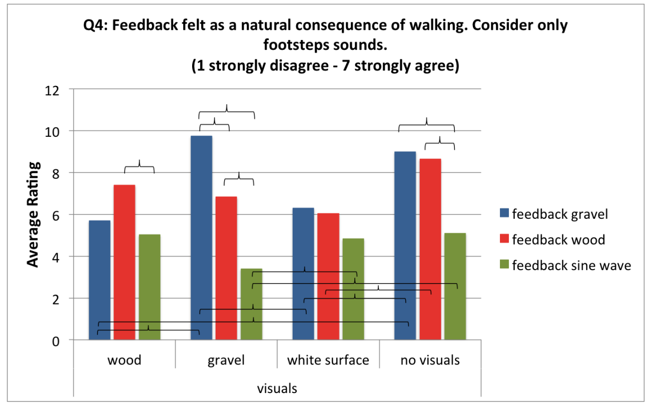

Figure 5: A visualisation of the experiment results for the Q4. The horizontal brackets present significant differences between conditions (p<0.05).

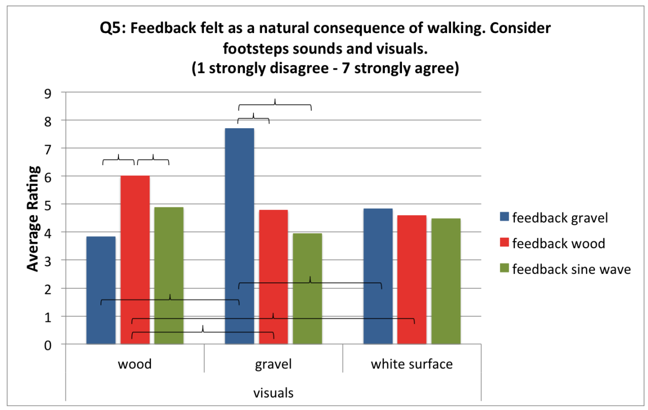

Figure 6: A visualisation of the experiment results for the Q5. The horizontal brackets present significant differences between conditions (p<0.05).

3.2 Questionnaire

The results of the six questionnaire items are summarized in Table 1. The analysis of ordinal data was performed by means of Friedman's ANOVA and the Wilcoxon signed-rank test (Table 2). These tests revealed several interesting effects. Significant differences between conditions were found for the data collected as the answers to Q2, Q4, Q5, and Q6. The results of the post-hoc tests are visualized in Figures 4 to 7.

Q2 (It was easy to walk while listening to the sounds of footsteps and watching visuals) revealed the lowest ratings (easy) in the conditions where the footsteps sounds and visuals were congruent and when the ecological feedback was presented (no visuals conditions) (Figure 4). This effect was as well proven by test of correlation (Spearman) between answers for Q2 and Q6 (Table 3) which suggested that higher ratings of perceived congruence were accompanied by a sensation of the walk being easier.

Despite the fact that the participants were asked only to judge the naturalness of the footsteps sounds in relation to Q4, their answers for the same sounds of footsteps varied depending on what visuals the sounds were combined with. Naturalness was rated higher when the sounds and visuals were congruent (e.g. the sound of gravel and the sight of a gravel path). When the sounds were presented without visuals, gravel and wood were rated as significantly higher than sine wave sound. Adding matching visuals to the gravel sound increased the ratings of footsteps naturalness, but the difference was not significant. Adding matching visuals to the wood sounds lowered the rating, but again the difference was not significant. Notably, some participants mentioned that they recognized both auditory and visual feedback as being wood, but they believed it to be different types of wood. We did not note similar comments in relation to gravel-matching case. Adding white surface to the footsteps sounds generally lowered the ratings of naturalness of gravel and wood feedback, but not sine wave.

Finally, Table 4 presents a summary of the participants' responses to the question asking them to identify the material they had walked on after each condition (Q7). Particularly, it summarizes the number of times the participants responses matched either the visual or auditory feedback. Responses that did not match the feedback presented in either of the two modalities have been omitted. Moreover, we have not included responses pertaining to conditions involv-

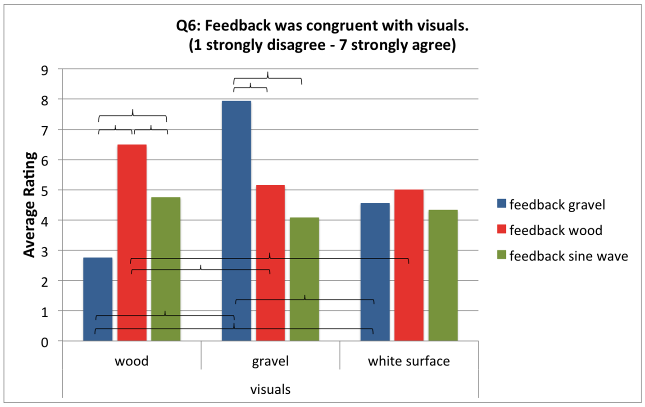

Figure 7: A visualisation of the experiment results for the Q6. The horizontal brackets present significant differences between conditions (p<0.05).

Visuals	Audio	Q1	Q2	Q3	Q4	Q5	Q6
wood	gravel	8.9	9.3	8.5	5.7	3.8	2.8
	wood	8.2	6.5	8.3	7.4	6.0	6.5
	sinusoid	9.3	7.5	8.8	5.0	4.9	4.8
	silence	6.6	6.7	8.6	-	-	-
gravel	gravel	8.7	5.4	6.8	9.8	7.7	7.9
	wood	7.6	7.9	9.5	6.8	4.8	5.2
	sinusoid	7.8	9.9	10.4	3.4	4.0	4.1
	silence	8.5	7.2	9.3	-		-
white	gravel	9.1	8.0	7.0	6.3	4.8	4.6
	wood	10.3	10.0	7.4	6.0	4.6	5.0
	sinusoid	8.5	10.7	9.3	4.8	4.5	4.3
	silence	9.7	9.9	7.7	-	-	-
none	gravel	9.2	6.4	8.2	9.0	-	-
	wood	7.8	6.6	8.7	8.7	-	-
	sinusoid	9.5	8.2	9.5	5.1	-	-
	silence	6.7	-	8.2	0.0	-	-

Table 1: Summary of the mean ratings for each question across the different conditions.

Questions	χ^2	p
Q1	19.96	0.173
Q2	46.88	< 0.001
Q3	18.60	0.233
Q4	66.59	< 0.001
Q5	33.67	< 0.001
Q6	52.33	< 0.001

Table 2: Summary of the results of Friedman's ANOVA test for questionnaire data.

ing feedback explicitly designed not to represent a particular surface (the equivocal white surface and sinusoid). The reason being that there was no way to determine if the verdict indeed matched the surfaces.

It is worth noting that almost all participants correctly identified the materials in the two congruent cases; i.e., 18/20 in case of wood and 19/20 in case of gravel. With respect to the incongruent cases there is little difference between the two materials, but the participants verdicts appear to be slightly more dominated by the visual feedback compared to the auditory feedback. Lastly, it is interesting to note that all participants identified the surface as being wood in the visuals only condition involving a wooden floor, while slightly fewer correctly identified the gravel surface. Contrarily, in the auditory only conditions, all participants correctly identified the gravel while far fewer correctly identified the wooden floor based on the sound.

Even though we omitted the responses related to the ambiguous feedback types, it is interesting to note that some of the participants identified the surface as being snow when exposed to a combination of gravel footstep sounds and the white surface. However, overall there was no difference within white surface visuals category in ratings of congruence (Figure 7).

4. DISCUSSION

In our previous experiments [11, 12, 13], we showed that different sounds of footsteps can influence the preferred pace of a walker. We have been testing feedback sounds which vary in two main dimensions: ecological—non ecological and aggregate—solid. The meaning encapsulated in the sounds and events, where they come from as well as the structure of the sound and clear point of synchronization, have an influence on the walker's choice of preferred pace. In [11], we added additional soundscape sounds to explore the hypothesis that more meaningful sounds will influence the choice of preferred pace. Our hypotheses were proven. In the present study we hypothesized that additional visual stimulation would cause similar effects. We observed that footsteps sounds, as before, influenced the walking pace, but the effect was smaller than in the previous studies, and we did not observe any significant effect of visuals on the average preferred pace. This could be caused by the general lack of this effect, but it also seems possible to offer alternate explanations. The setup used for the current experiment was designed to be as similar as possible to the one used in our previous studies on the influence of the various footsteps sounds on rhythmic behaviour. Unfortunately, the use of the HMD in combination with aerobic stepper may have made our participants feel less comfortable than in previous studies since it forced them to stand on an elevated platform while blinded to real world stimuli. Moreover, the fact that the participants were required to hold on to the table during the walks, may also have influenced both the preferred tempo and the general naturalness of the experince. Indeed, it has been speculated that additional haptic feedback provided by the handrails on treadmills, may influence people's perception of visually presented speeds during treadmill-mediated virtual walking [21]. We suspect that these factors may have entailed that the participants did not feel free enough to walk in the pace they preferred (it may have been more like a 'safe' pace rather than the preferred one). However, even though the participants did not manipulate the preferred tempo as much as they would potentially when walking on a flat surface, we observed similar effects as in our previous studies [11, 12, 13].

A second, but not mutually exclusive, explanation is that the mere presence of the visuals influenced the preferred tempo. Since it has been demonstrated that individuals walking on a treadmill will change the walking speed in response to varying visual speeds [22, 28], it does seem possible that the visual feedback did have an influence. Notably,

Questions	p	Correlation
Q1 vs Q2	< 0.001	0.544
Q1 vs Q5	< 0.005	-2.13
Q2 vs Q4	< 0.001	-0.358
Q2 vs Q5	< 0.05	-0.204
Q2 vs Q6	< 0.05	-0.178
Q4 vs Q5	< 0.001	0.619
Q4 vs Q6	< 0.001	0.536
Q5 vs Q6	< 0.001	0.630

Table 3: Summary of the significant correlation between specified sets of data.

	Condition		Response matches	
	Visuals	Audio	Visuals	Audio
Congruent:	wood	wood	18	18
	gravel	gravel	19	19
Incongruent:	gravel	wood	10	7
	wood	gravel	10	8
Unimodal:	wood	silence	20	-
	gravel	silence	17	-
	none	gravel	-	20
	none	wood	-	12

Table 4: Summary of responses to Q7: Number of time the participants identified the surface they were walking on based on the visual and auditory feedback. Responses that did not match the feedback presented in either of the two modalities have been omitted.

the three visual environments only differed in terms of the ground material. All other visual cues producing optic flow were kept constant. Thus, it seems possible that the visuals did not differ sufficiently in order to produce variations in tempo. Moreover, if vision dominated audition, as it often does on spatial tasks [8], it seems possible that it might have minimized the previously documented effects of the auditory feedback.

An interesting result is the correlation identified between ease of walking and congruence of audio-visual stimuli. We observed the stimuli which the participants rated as more congruent also was perceived to be the stimuli which made the walking easier. Notably, several participants explicitly mentioned this effect when casually discussing their experience with the experimenter after completing the study. The effect appeared to be especially pronounced when both auditory and visual stimuli had clear meanings which did not make sense when combined (e.g. visual gravel and sound of wood). In other words, incongruent, ecological feedback seemingly made it harder for the participants to walk while listening.

We can compare two types of combination between introduced stimuli. One situation is when both auditory and visual stimuli have clear meaning (two ecological stimuli), and the second where one is equivocal and complemented with another stimulus with a clear meaning (ecological and non-ecological stimuli). The introduced white surface was supposed to have a role of the equivocal visual stimuli, which would not be congruent with any of the auditory stimulus. However, interestingly, we observed this surface combined with different auditory stimuli was interpreted as different materials. When gravel feedback was combined with equivocal white surface it was rated as significantly more congruent than when the same gravel stimuli was combed with visual wood floor. It means that our participants could imagine situation when white surface could generate this kind of sounds but it was almost impossible when combined with wooden floor. Most notably this combination led to some participants identifying the surface as snow. Presumable, because the the color of the white surface resembled snow, and because both snow and gravel are aggregate surfaces, thus producing sounds that bear some semblance. Similar situation appeared for the wood sound combined with each of the auditory stimuli. On the other hand, we presented sine wave sound to test the effect of non ecological (artificial) sound presented as feedback of the footsteps. There was no difference when combined with any of the visuals. Interesting observation is that participants in each trial tried to match what they experience with real situation, illustrating to how great a length people will go to in order to make sense of stimuli that need not be easily explained.

In this experiment we presented the walking participants with a very simple situation in order to test the effect of visual and auditory stimuli representing different types of surfaces. We purposely did not consider virtual environments with more complex visuals since we wanted to investigate the influence of the surface alone rather than the environment as a whole. This leaves at number of potential directions for future research. The first is to test similar scenario where people could feel more comfortable and walk more freely. This would give us the possibility to carefully investigate the influence of visuals on preferred walking pace. Secondly, it would be relevant to explore more scenarios involving much more complex and rich visual and auditory stimuli. Moreover, it would be interesting to explore if the observed effects translate to scenarios where the user is physically walking rather than stepping in place.

Finally, the current study highlights the importance of properly combining multimodal stimuli when building virtual environments. This knowledge could be applicable to entertainment as well as exercise and rehabilitation field. Introducing virtual environments for motivation to exercise or rehabilitation is a very challenging task. Improper combination of visual and auditory stimuli can lead to undesirable effects and potentially demotivate the user from exercising.

5. CONCLUSIONS

In this paper we presented results of the experiment where auditory and visual ecological and non ecological stimuli were presented. We aimed to investigate how they influence rhythmic walking performance and affect perceived ease and naturalness of walking. Additionally, we checked the perceived level of congruence between chosen visual and auditory stimuli and the correlation between rated congruence and ease of walking. Due to the limitations of our setup, where participants did not feel comfortable enough we can not conclude definitely if added visual stimulation can influence preferred walking pace. The averaged pace was affected by the footsteps sounds. The questionnaire data revealed that perceived congruence is correlated with ease of walking. The obtained results are interesting in a context of entertainment and exercise/rehabilitation with a help of VR.

A number of potential directions for future research exist in relation to the interplay between sound, visuals, and rhythmic actions during virtual walking. First and foremost, it will be interesting for future work to explore if the findings of the current and our previous studies applies to other rhythmic walking interactions (i.e., treadmill and real walking). With future studies we would like as well to add more elements to the visual and auditory scenes. That could raise the ecological validity of the experiment setup in controlled environment. Furthermore, since visually presented speeds may be perceived differently during real and virtual walking, it would be interesting to explore if the addition of sound can influence the perception of visual speeds, and it would be relevant to determine if walking speeds presented exclusively using sound also are perceptually distorted. Finally, if the effects are confirmed we would like to experiment with patients who require gait rehabilitation and see if the visual and auditory stimulation can positively influence their performance.

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