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It takes me back: The mnemonic time-travel effect

[1,2]Aleksandar Aksentijevic, [1]Kaz R. Brandt, [1]Elias Tsakanikos and [1]Michael J. A. Thorpe

[1]Department of Psychology, University of Roehampton

[2]Birkbeck, University of London

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Corresponding author:

Aleksandar Aksentijevic, Department of Psychology, University of Roehampton, Whitelands College, Holybourne Avenue, London SW154JD, United Kingdom. E-mail: a.aksentijevic@roehampton.ac.uk

Abstract

Given the links between motion and temporal thinking, it is surprising that no studies have examined the possibility that transporting participants back mentally towards the time of encoding could improve memory. Six experiments investigated whether backward motion would promote recall relative to forward motion or no-motion conditions. Participants saw a video of a staged crime (Experiments 1, 3 and 5), a word list (Experiments 2 and 4) or a set of pictures (Experiment 6). Then, they walked forward or backwards (Experiments 1 and 2), watched a forward- or backward-directed optic flow-inducing video (Experiments 3 and 4) or imagined walking forward or backwards (Experiments 5 and 6). Finally, they answered questions about the video or recalled words or pictures. The results demonstrated for the first time that motion-induced past-directed mental time travel improved mnemonic performance for different types of information. We briefly discuss theoretical and practical implications of this "mnemonic time-travel effect".

Keywords: Mental time travel, episodic memory, context reinstatement, eyewitness memory, mental time line

1.1 Introduction

Time and space tend to be experienced as interrelated across different societies and cultures (Keefer, Stewart, Palitsky, & Sullivan, 2017). Time, that most abstract of mental phenomena does not possess its own referential system—unlike space which is based on the interaction with the environment. To quote Galton (2011): "… time, as a fundamental and inalienable feature of our experience, will ultimately resist our attempts to describe it as anything else (p. 695)." The ineffability of time notwithstanding there is strong need to express time in terms of less abstract ideas. One influential hypothesis (e.g. Bender & Beller, 2014; Boroditsky 2000) suggests that the abstract concept of time is grasped and operationalized in terms of a more experientially available concept of space. A substantial body of research has shown that the direction of spatial movement influences the temporal location of individuals' thoughts in that forward motion encourages future thinking and backward motion facilitates thoughts about the past (Boroditsky & Ramscar, 2002), that thinking about the future or past tends to affect postural sway (Miles, Nind & Macrae, 2010) and that backward vection (stimulus-induced sense of motion; Ash, Palmisano & Kim, 2011; Dichgans & Brandt, 1978; Palmisano, Allison, Schira & Barry, 2015) can elicit past thinking while forward vection facilitates future thinking (Miles, Karpinska, Lumsden & McRae, 2010). Closely related to this is the concept of the subjective time line (e.g. Hartmann & Mast, 2012; Rinaldi, Locati, Parolin, Bernardi & Girelli, 2016)—an imaginary line which orders our experience by passing through our body centrally in both directions with the future portion extending in front of the body and the past portion extending to the back. Although not universal, the association between the past and the dorsal space is an inherent part of many cultures (e.g. Nuńez & Cooperrider, 2013).

It is along this line that mental time travel (MTT; Tulving and Thompson, 1973, Tulving, 1985) takes place. MTT refers to the assumed ability of the mind to “travel” both towards the past and the future. The future MTT refers to the ability to “cast one’s mind” into the future and contemplate possible outcomes and experiences. It is critical for decision making and motivational control of impulsive decisions and behaviours (e.g. Noël, Saeremans, Kornreich, Jaafari, D’Argembeau, 2017). On the other hand, the most intensively investigated aspect of MTT is the past-directed MTT or episodic memory—the mind’s journey towards the experienced past which enables us to remember spatial, temporal and personally-relevant aspects of the experience (e.g. Tulving, 2002). Episodic memory is crucial for the construction of the self (Klein, 2001) and represents the mental “anchor” for thought, action and prediction of future events.

It is worth emphasizing that the experience of space-time is dynamic. Caruso, van Boven, Chin and Ward (2013) discovered that when judging future or past temporal intervals, observers reliably underestimated the former. Aksentijevic and Treider (2016) made changes to this design and elicited future and past estimates from single subjects. They found both contraction and dilation of time-distance estimates with real and imaginary motion but only with respect to the past. Specifically, when moving forward, estimates lengthened with regard to the past but remained unaffected vis-à-vis the future. Backward motion led to a dilation of future and contraction of past estimates relative to the control/no-motion condition. By contrast, forward motion had no effect on past estimates. The authors proposed that the observed past-directed Doppler-like effect could imply that backward motion-induced past-directed MTT could bring the individual closer to the time of encoding leading to improvements in memory performance. One explanation is that recall of an event involves episodic recollection of a specific context (e.g. environmental and ambient cues, emotional states) and numerous studies have demonstrated that successful retrieval depends not only on the degree of overlap between encoding and retrieval conditions (Morris, Bransford, & Franks, 1977; Tulving & Thompson, 1973) but that reinstating encoding context at retrieval enhances episodic recollection (Dewhurst, Conway & Brandt, 2009).

Thus, the rationale for the present study is the possibility that some of this recall-relevant contextual information could be recaptured by mentally transporting the participant back in time towards a point at which they experienced it—a form of reverse context reinstatement procedure (Godden & Baddeley, 1975). As shown by a recent behavioural/scanning study, successful mnemonic techniques rely on associating to-be-remembered stimuli with loci within spatial routes and remembering involves *retracing one's steps* through the route in order to access individual items (Dresler et al., 2017).

Since MTT can be induced by physical and imaginary motion (e.g. Boroditsky & Ramscar, 2002) and vection (Caruso et al., 2013, study 3; Miles, Nind & McRae, 2010), any of these methods could be used to take a participant "back" in time. The aim of the present study was to test the hypothesis that backward motion—either real (Experiments 1 and 2), simulated (Experiments 3 and 4) or imaginary (Experiments 5 and 6)—would improve the recollection of different types of information, namely a dynamic scene (Experiments 1, 3 and 5), words (Experiments 2 and 4) and pictures (Experiment 6). Recent findings of a direct link between past-directed thinking and backward physical motion (Rinaldi, Locati, Parolin, Bernardi & Girelli, 2016) suggest a very close link between past-directed thinking and backward motion. Specifically, their participants correctly and rapidly initiated backward steps in response to past-associated words and made forward steps following future-directed words. Thus, our experiments could be seen as the obverse of Rinaldi et al.'s study—rather than demonstrating that thinking about the past makes us want to move backwards, we investigated the possibility that moving backwards would facilitate remembering the (near) past. Consequently, the scope of the current set of experiments was a broad yet systematic experimental survey of the MMT-related stimulus space carried out in order to find out if the mental journey into the past facilitated mnemonic performance.

The current study possesses a clear theoretical and methodological structure—specifically a 3 x 2 factorial structure with variables type of motion (real, virtual, imaginary) and the type of the memory stimulus (dynamic, static). The latter is incompletely factorised with two experiments (2 and 4) investigating memory for words and one (Experiment 6) probing memory for pictures (see Table 1). Thus, the study moves from the most realistic motion condition tested on a dynamic stimulus (Experiment 1) to the least realistic condition tested on static stimuli (Experiment 6) allowing us to explore the stimulus space fairly comprehensively and systematically. Based on the results of Aksentijevic and Treider (2016) and Rinaldi et al. (2016), we predicted a significant memorial advantage for backward motion relative to forward and control conditions. Although those same results might predict a worsening of mnemonic performance with forward motion, a pilot study of imaginary motion and word recall revealed no difference relative to the no-motion condition. Finally, given the importance of optic flow for motion perception (e.g. Lee, 1980), we hypothesized that optic flow (without the accompanying sensation of motion) would be sufficient to trigger past-directed thinking.

Table 1.

Factorial structure of the present study

Motion type	Memory stimulus	
	Dynamic	Static
Real	Experiment 1*	Experiment 2**
Virtual	Experiment 3*	Experiment 4**
Imaginary	Experiment 5*	Experiment 6***

Note. Memory stimulus: = video, ** = words, *** = pictures.*

2.1 Experiment 1: Physical motion and eyewitness memory

2.1.1 Method

1.2.1.1 Participants and design. All experiments were approved by the Ethics Committee of the Department of Psychology, University of Roehampton and were carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki. Participants in all experiments received either course credits or book vouchers in lieu of remuneration.

114 volunteers took part (52 male, mean age = 27.43, *SD* = 11.32). 80 participants (70%) had English as their first language and as in all the reported experiments all had normal or corrected-to-normal vision. All participants provided informed consent and retained the right to withdraw at any point. Experiment 1 employed a 1-way between-participants design with independent variable motion direction (forward, backward, control/no motion). Sample size was estimated using G-Power software (Faul, Erdfelder,

Lang & Buchner, 2007). Effect size was estimated based on the findings of Aksentijevic and Treider (2016) where both real and imaginary motion produced a large effect, $f = .82$. For a one-way ANOVA model, sample size of 114 (cells size of 38) was required to detect a large effect ($f = .40+$) at $p = .001$ with the power of .90.

2.1.1.2 Apparatus and stimuli. Given the theoretical and practical importance of eyewitness memory and its sensitivity to mental context reinstatement (Smith-Spark, Bartimus & Wilcock, 2017), participants were presented with a video of a staged bag-snatching scene in which a woman walks into a park, sits on a park bench to have lunch, is distracted by a confederate and has her bag stolen by a passer-by. At the end, a brief exchange ensues between the woman and the confederates (Oxford Education, 2012). A clip (duration: 1:28 minutes) was extracted from the original video (total duration: 3:22 minutes; start = 0:05 minutes) using Adobe Premiere editing suite and saved in .avi format. The video contained sound and was presented on a laptop. The dimensions of the video were 25.9 x 19.5 cm subtending a visual angle of 24.36 x 18.46 degrees from a viewing distance of 60 cm.

The retention of the relevant features of the crime scene was tested by means of a 20-item binary-choice questionnaire asking about different aspects and details of the crime scene (Appendix 1). The order of the questions roughly followed the event sequence. Each correct answer was awarded a single point. The distractor activity was implemented via an Android app (“Pure Sudoku”). The walking tempo was maintained by an Android metronome app (metronome is commonly used to guide stride tempo in experiments employing walking (e.g. Styns, van Noorden, Moelants & Leman, 2007).

2.1.1.3. Procedure. Participants provided demographic information, informed consent and were then briefed and assigned to one of the conditions. They were shown the crime video and then engaged in a 10-minute distractor task (solving Sudoku puzzles). Following this, participants were asked to walk 10 meters towards a fixed target (e.g. a chair or a bucket; see Aksentijevic & Treider, 2016 for detailed instructions). The starting point was marked off with duct tape. Walking tempo of 60 bpm was maintained throughout the activity. Participants could walk either forward or backward (they were offered assistance in the latter condition). They were placed on the starting point and started walking after saying "now". The walking tempo was controlled by the metronome. In the backward condition, participants were asked to turn away from the target and start walking. They stopped when the experimenter indicated that they had reached the target. The control group remained in place for an extra two minutes. This was done in order to compensate for the time active participants would spend on receiving instructions, familiarising themselves with the metronome and walking pace, executing the task and asking questions/commenting on the activity. Then, all participants were asked to complete the memory questionnaire within 3 minutes in any order. At the end, they were fully debriefed. An individual session lasted between 30 and 35 minutes.

2.1.2 Results

The overall mean number of correct answers was 14.75 (74%), $SD = 2.78$ (see E1 data.sav). No correlation was found between age and performance, $r = -.10$, $p = .294$, and no differences in performance were observed with regard to EFL, $t(112) = 0.92$, $p = .360$. However, there was a marginally significant recall advantage for male, $M = 15.3$, $SD = 2.43$, relative to female participants, $M = 14.3$, $SD = 2.93$, $t(112) = 1.95$, $p = .053$. To test the main hypotheses, a one-way between-participants ANOVA was performed on the mean number of correct answers. This revealed a highly significant effect of motion condition, $F(2,111) = 9.37$, $p < .001$, $f = 0.40$ (Figure 1a). The power of the study was .98. A priori t tests confirmed a significant backward motion advantage relative to forward motion, $t(74) = 3.13$, *p* = .002, and control condition, *t*(74) = 4.28, *p* < .001 (*d* = 0.70 and 0.98) respectively. No differences were observed between the forward and control conditions, *t*(74) = 1.16, *p* = .249.

3.1 Experiment 2: Physical motion and word recall

3.1.1 Method

3.1.1.1 Participants and design. 114 participants took part in Experiment 2 (94 female, mean age = 20.69 years, *SD* = 4.57). 79 participants (69%) had English as their first language. The design was identical to that employed in Experiment 1. The dependent variable was the mean number of recalled words.

3.1.1.2 Apparatus and stimuli. A 20-word list was created from the original set of 74 high-frequency bisyllabic words from the MRC Psycholinguistic Database (http://www.psych.rl.ac.uk/; see data file E2 E4 word parameters.sav for a list of parameter values for the entire set). The summary statistics for the list were as follows: concreteness index over 500, Kucera-Francis frequency index over 50, imageability index over 400. The mean parameter values for the list were as follows: mean concreteness = 580.35, *SD* = 29.14; mean frequency = 144.80, *SD* = 178.12; mean imageability = 591.30, *SD* = 37.22; mean number of letters = 5.85, *SD* = 0.99; mean syllable length = 2.93, *SD* = 0.71 (see E2 E4 word parameters.sav for a detailed breakdown of parameter values for individual words). The words were rendered in Arial font (size 44) and presented as a sequential list using E-Prime software. Each word was presented for 2 seconds followed by a 1-second interval. From the viewing distance of 60 cm, the shortest word (baby) subtended 1.90 degrees of visual angle and the longest one (shoulder), 4.30 degrees. The remaining stimuli were identical to those used in Experiments 1 and 3.

3.1.1.3 Procedure. After completing preliminary tasks, participants were presented with a word list. This was followed by 10 minutes of distractor activity (Sudoku) and the walking task. Then, the participants were asked to write down as many words as they could remember in any order within 2 minutes. Finally, they were thanked and debriefed.

3.1.2 Results

Data from one participant were removed due to failing to recall a single word. No differences in recall were found with regard to gender, $t(111) = .02$, $p = .984$, or EFL, $t(110) = 1.47$, $p = .143$. Further, there was a marginally significant negative correlation between age and performance, $r = .17$, $p = .079$. Overall, the mean recall rate was 8.38 words (42%, $SD = 2.90$). A one-way between-participants ANOVA revealed a highly significant effect of motion condition, $F(2,112) = 8.80$, $p < .001$, $f = 0.40$ (Figure 1b; E2 data.sav). The observed power of the experiment was .97. The advantage for backward motion over the forward and control groups was confirmed by means of t tests, $t(65.83) = 4.18$, $p < .001$ and $t(74) = 2.44$, $p = .017$ ($d = 0.97$ and 0.56) respectively. No significant difference was observed between the latter two conditions, $t(73) = 1.64$, $p = .105$.

4.1 Experiment 3: Optic flow and eyewitness memory

4.1.1 Method

4.1.1.1 Participants and design. As in experiment 1, 114 volunteers (62 female, 45 male, 7 other) took part (mean age = 28.90 years, $SD = 12.65$). 66 participants (58%) had English as a first language. The design was the same as that used in Experiments 1 and 2. The dependent variable was the mean number of correct answers.

4.1.1.2 Apparatus and stimuli. The crime-scene video and Sudoku app were identical to those used in Experiment 1. The optic flow-inducing video consisted of a train journey filmed in daytime from the back platform of a train (moving backwards from the observer's perspective; Orcatv, 2011). It was selected for the fact that the motion was smooth and that it contained no clues as to the direction of travel such as voices, moving vehicles, people or animals. The line of sight was roughly located at the centre of the scene. The video was edited in Adobe Premier by extracting a 2-minute clip from the original video (total duration: 6:33 minutes; start of the clip: 0:50 seconds); the sound was normalized and 1-second fade-in and fade-out ramps were added to the start and the end of the clip. The forward version of the video was created in Adobe Premier by reversing the backward clip. The two versions were completely symmetrical so that it was impossible to determine which of the two clips was the original recording. Both clips were saved in .avi format. The dimensions of the video were 26.7 by 19.9 cm, producing a visual angle of 25.5 by 18.83 degrees from a distance of 60 cm. The velocity of the train was estimated at approximately 8 m s^{-1} using Kinovea software (https://www.kinovea.org).

4.1.1.3 Procedure. At the start of each session, participants were briefed, asked to sign a consent form and complete a demographic questionnaire. Following this, the participants were informed that they would watch a brief video. As a next step, participants were given 10 minutes to complete a distractor task—a set of Sudoku puzzles. Then, the forward and backward groups were shown the motion video (the horizontal visual angle of 25 degrees was maintained throughout). The control group remained in place for an extra two minutes. Then, all participants were asked to complete the memory questionnaire within 3 minutes. At the end, they were fully debriefed. An individual session lasted between 30 and 35 minutes.

4.1.2 Results

The mean number of answers was 13.86 (69%, *SD* = 2.53). The best recall performance was observed for question 15 (93%) and as in the previous experiment, question 17 produced the lowest number of correct answers (33.3%). As in Experiment 1, no effects of demographic variables were observed (E3 data.sav). Specifically, age did not affect performance, $r = .01$, $p = .923$, and the same was observed for gender, $t(105) = 1.38$, $p = .171$, as well as English as the first language, $t(112) = 1.22$, $p = .224$.

A highly significant effect of motion condition was revealed by a one-way between-participants ANOVA, $F(2,111) = 7.07$, $p = .001$, $f = 0.35$ (Figure 1c). The observed power was .92 and comparisons between individual conditions revealed a significant enhancement in performance for the backward condition relative to the forward and control conditions, $t(74) = 3.25$, $p = .002$ and $t(74) = 3.38$, $p = .001$ ($d = 0.74$ and 0.77), respectively. There was no difference between the forward and control conditions, $t(74) = 2.80$, $p = .782$.

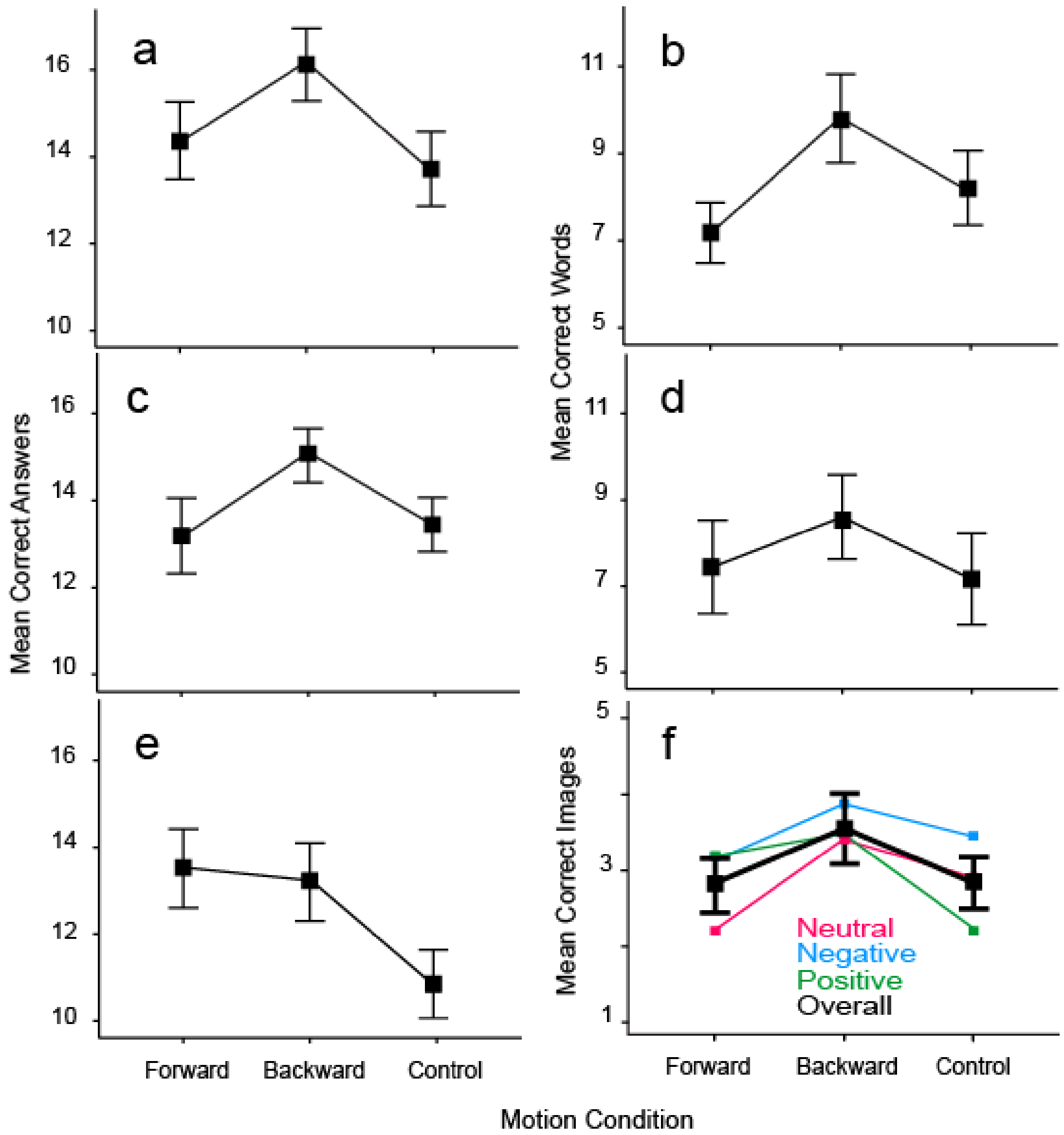

Figure 1. Memory performance as a function of motion condition in experiments 1 - 6 (a - f with "a" representing Experiment 1 and "f", Experiment 6). Error bars represent 95% confidence intervals.

5.1 Experiment 4: Optic flow and word recall

5.1.1 Method

5.1.1.1 Participants and design. 25 volunteers took part in the experiment (21 female; mean age = 20.48 years, *SD* = 1.53). 18 participants (72%) had English as their first language. The study employed a one-way repeated-measures design with variable motion direction (forward motion, backward motion, no motion/control). The dependent variable was the mean number of recalled words. Sample size was estimated using G-Power software (Faul et al., 2007). The sample size required to detect a large effect in a repeated-measures ANOVA with a power of .80 at p = .001 was 17. Acting conservatively, we increased the sample size to 25.

Table 2.

Summary parameters for word lists used in Experiment 4

List	Concreteness	Imageability	Frequency	Number of letters	Syllable length
1	578.27 (30.57)	588.73 (41.32)	168.20 (201.01)	6.13 (0.83)	3.07 (0.68)
2	571.20 (19.85)	587.33 (34.94)	151.73 (68.86)	6.13 (1.30)	3.07 (0.88)
3	565.31 (35.16)	580.81 (45.92)	150.19 (115.56)	5.88 (0.96)	2.94 (0.74)

Note. Standard deviations in parentheses. No significant between-list differences were observed (all p > .400).

5.1.1.2 Apparatus and stimuli. Stimuli were presented on a laptop computer. Fixed head position was maintained by means of a chin rest and participants' eye line was aligned with the centre of the screen. As in Experiment 2, a set of high-frequency bisyllabic words was created using the MRC Psycholinguistic Database (http://www.psych.rl.ac.uk/). All words had concreteness ratings over 500, Kucera-Francis frequency index over 50 and imageability ratings over 400. From this, three different 15-word lists were created (see Table 2 for a summary of list properties and also E2 E4 word parameters.sav). The presentation in the form of a slide show was created in Microsoft Power Point (Microsoft Inc.). The words were rendered in black lower-case Arial font (size 44) on a white background and were centred on the screen. Each word was presented for 2 seconds, followed by a 2-second interval. From the viewing distance of 45 cm, the shortest word (fire) subtended 1.53 and the longest (breakfast), 5.10 degrees. The motion videos were the same as those used in Experiment 3 and they subtended 33.05 by 25 degrees.

5.1.1.3 Procedure. At the start of each session, participants were briefed, asked to sign a consent form and complete a demographic questionnaire. Following this, the participants were informed that they would see a list of words which they should try to remember. Each word was presented for two seconds and replaced by a 2-second interval. As a next step, participants were given 5 minutes to complete a distractor task—a Tetris puzzle administered via a mobile phone application. Following this, they were presented with the video. Then, participants were asked to recall as many words as they could by writing them down in any order within two minutes. Following this, they took part in two remaining conditions. The order of conditions and word lists was counterbalanced across participants. An individual session lasted approximately 30 minutes.

5.1.2 Results

The overall mean number of recalled words was 7.33 (52%, *SD* = 7.20; see E4 data.sav). No difference in performance was observed between native and non-native speakers, $t(23) = .21$, $p = .840$, or male and female participants, $t(23) = 1.05$, $p = .306$. No correlation was found between age and performance, $r = -.32$, $p = .120$. A one-way within-participants ANOVA with variable motion direction (forward, backward, no motion/control) revealed a highly significant difference among conditions, $F(2,48) = 17.23$, $p < .001$, $f = 0.84$ (Figure 1d). The observed power was 1. The effect size was over double that in Experiment 3 suggesting that increasing the visual angle and shortening the distractor period led to an increase in the effectiveness of the stimulus. There was a highly significant advantage in the backward condition relative to the control, $t(24) = 5.43$, $p < .001$, $d = 1.54$ and forward condition, $t(24) = 5.24$, $p < .001$, $d = 1.50$. The within-participants *d* values were calculated using Cohen's (1988) correction for the correlation between conditions—dividing the standard *d* value by the square root of 1 - *r*. There was no difference between the forward and control conditions. Only two participants performed better in the forward relative to backward condition, $t(24) = .96$, $p = .347$.

6.1 Experiment 5: Imaginary motion and eyewitness memory

6.1.1 Method

6.1.1.1 Participants and design. 114 volunteers (76 female, 37 male, 1 other) took part in the experiment. The mean age was 21.35 years, $SD = 2.06$. 85 participants (75%) had English as their first language. The design was a 1-way between-participants design with variable motion condition (forward, backward, control). The dependent variable was the mean number of correctly answered questions.

6.1.1.2 Apparatus and stimuli. Testing environment, apparatus and stimuli were identical to those used in Experiments 1 and 3.

6.1.1.3 Procedure. At the start of each session, participants were briefed, asked to sign a consent form and complete a demographic questionnaire. Following this, the participants were informed that they would watch a brief video. They were told to focus and the experimenter was present in the room throughout. As a next step, participants were given 10 minutes to complete a distractor task—a set of Sudoku puzzles. Following this, participants were taken from the cubicle into corridor. A target (e.g. a bucket) was placed 10 meters away from the starting point marked with duct tape.

The participant was placed at the starting point and instructed to close their eyes and say “now” once they were ready to proceed. The metronome was started and the participants were required to say “stop” once they felt they had reached the target (see Aksentijevic & Treider, 2016 for procedural details and detailed instructions). In the backward condition, participants were asked to turn away from the target and begin their imaginary backward walk followed by a metronome. They stopped when they felt they had reached the target. The control group remained in place for an extra two minutes. Then, all participants were asked to complete the memory questionnaire within 3 minutes in any order. At the end, they were fully debriefed. An individual session lasted between 30 and 35 minutes.

6.1.2 Results

Six participants failed to engage with the task or provide any correct answers and their data were removed from analyses. The mean recall score was 12.52 correct answers (63%, SD = 2.75; E5 data.sav). Question 17 produced the lowest scores (49%), while the highest score was obtained on questions 15 and 20 (89%). No correlation between age and recall was observed, $r = .00$, $p = .996$, and recall scores did not differ between genders, $t(105) = 0.48$, $p = .630$. Equally, a t test for EFL revealed no significant differences in performance, $t(106) = 1.28$, $p = .204$. The main one-way ANOVA revealed a significant effect of motion, $F(2,105) = 12.92$, $p < .001$, $f = 0.50$ (Figure 1e). The observed power of the experiment was 1. A priori t tests revealed that the mnemonic performance in the forward and backward conditions was highly significantly superior to that in the control condition, $t(70) = 4.63$, $p < .001$ and $t(70) = 4.31$, $p < .001$ ($d = 1.09$ and 1.02 respectively). No difference was observed between the forward and backward conditions, $t(70) = 0.50$, $p = .619$.

Additional analyses were performed across experiments 1, 3 and 5 which were methodologically identical. Mean overall recall was 13.74 correct answers (69%), $SD = 2.81$.

Question 15 (gender of the perpetrator) produced best performance (91.4%) and item 17 (colour of perpetrator's shoes) the worst (42.3%). Analysis of recall performance revealed a highly significant effect of experiment, $F(2, 333) = 19.53$, $p < .001$; $f = 0.34$. Overall, recall was significantly better in the real-motion condition (Experiment 1) relative to optic flow (Experiment 3), $t(226) = 2.44$, $p = .016$, and optic flow produced a significantly better performance relative to imaginary motion (Experiment 5), $t(220) = 3.89$, $p < .001$. At the same time, Experiment 5 produced the largest effect size out of the three ($f = 0.50$). Participants in Experiment 5 were younger relative to those in Experiments 1 and 3, $F(2,333) = 17.77$, $p < .001$. Further, significantly more participants in Experiment 5 had English as a first language, $F(2,333) = 5.82$, $p = .003$. Age could not have affected performance as no correlation between the two variables was observed, $r = .06$, $p = 347$. Equally, no effects on recall were found with regard to EFL, $t(334) = 1.33$, $p = .184$. As concerns gender, males tended to perform slightly better than females, $M = 14.16$ (71%), $SD = 2.77$, compared with $M = 13.44$ (67%), $SD = 2.84$, respectively, $t(326) = 2.28$, $p = .023$.

7.1 Experiment 6: Imaginary motion and picture recall

7.1.1 Method

7.1.1.1 Participants and design. 60 volunteers took part in the experiment (53 female, mean age = 20.53, *SD* = 5.15). 45 participants (75%) had English as their first language. The design was a 3 x 3 mixed design with variables motion condition (forward, backward, control; between-participants) and emotional valence (positive, negative, neutral; within-participants). The dependent variable was the mean number of correctly recalled pictures. Given the very high observed power of Experiment 5, we estimated that 20 participants per cell would be sufficient to obtain sufficient power (.80+) for motion condition.

7.1.1.2 Apparatus and stimuli. 18 colour photographs of generic life scenes and containing people were used. The key criteria were easy recognisability and low confusability. Six pictures had a positive affective valence (babies, bride, party, graduation, Christmas dinner, gender reveal), six had a negative valence (car crash, funeral, flood, forensics, memorial, homeless people) and six were neutral (café, railway station, supermarket, central London, on the bus, hiking).[1] Using Adobe Photoshop, the pictures were cropped and scaled to a uniform size (24.87 x 16.80 cm) which resulted in a visual angle of 23.25 x 15.56 degrees from the viewing distance of 60 cm. A Kruskal-Wallis 1-way ANOVA did not reveal any inter-category differences in terms of image luminosity or red, green and blue intensity (see E6 image parameters.sav). In order to confirm category differences with regard to emotional valence, 18 participants rated each image on a 7-point scale (1= very positive, 4 = neutral and 7 = negative). A Kruskal-Wallis test confirmed a highly significant difference between the valence categories ($p < .001$). A Mann-Whitney U test indicated that positive pictures were rated significantly higher than the neutral ($p = .002$) and negative ones. ($p = .002$). Negative pictures were rated significantly lower relative to the neutral ones ($p = .002$; see E6 valence ratings.sav).

Microsoft PowerPoint presentation was used to present the pictures on a computer screen. Each image was presented for five seconds. In order to eliminate serial-position effects, image order was varied across participants using a random number generator. A Sudoku task was administered to participants during the distractor interval. An Android metronome app set at 60 beats per minute was used to control the speed of the imaginary walk.

7.1.1.3 Procedure. At the beginning of each session, participants were briefed, asked to read and sign a consent form and fill out a demographic questionnaire. They were made

[1] "Gender reveal" refers to a surprise party in which parent/s and/or friends and guests discover the gender of the (yet unborn) baby.

aware of the recall task. Following this, participants were shown the presentation and were instructed to pay attention to the pictures. Afterward, participants were given 10 minutes to complete a distraction task with the instructions to do their best even if they could not finish it and that it was not a test of ability. After the imaginary walking task (described in Experiment 5), participants were brought back into the testing cubicle and were asked to recall as many pictures as possible, by writing down a brief description of each image within three minutes in any order. An individual session lasted approximately 30 minutes.

7.1.2 Results

The most frequently recalled image was that of a funeral, (51 correct responses, 85%, *SD* = .36), and the least recalled was gender reveal, (18 correct responses, 30%, *SD* = .46; see E6 data by image.sav). Pairwise tests of differences between proportions across the three motion groups revealed no differences in group makeup with respect to gender or EFL (all $p > .400$). However, a small negative correlation was observed between age and negative image recall, $r(60) = -.28$, $p = .049$. Gender did not affect performance, $t(58) = 0.41$, $p = .687$, and no effects of first language or age were observed, $t(58) = 0.58$, $p = .563$ and r = -.16, $p = .221$, respectively. The overall average number of recalled pictures was 9.18 (51%; *SD* = 2.68). A 3 x 3 mixed-design ANOVA with variables motion direction and emotional valence revealed a significant main effect of motion direction, $F(2,57) = 5.14$, $p = .009$, $f = 0.42$, as well as a main effect of valence, $F(2,114) = 4.16$, $p = .018$, $f = 0.27$. Finally, there was a significant valence by motion direction interaction, $F(4,114) = 2.79$, $p = .030$, $f = 0.31$ (Figure 1f). As predicted, the observed power for motion condition was .81.

More information was recalled in the backward condition relative to the forward or control conditions, $t(38) = 2.68$, $p = .011$, $d = 0.84$ and $t(38) = 2.61$, $p = .013$, $d = 0.82$, respectively. There was no difference between the control and forward conditions, $t(38) =$

.14, *p* = .889. Overall, more negative than neutral or positive information was recalled, *t*(59) = 2.64, *p* = .011, *d = 0.44* and *t*(59) = 2.48, *p* = .016, *d* = .037 respectively (a negativity bias which could be related to arousal; e.g. Scherer, Dan & Flykt, 2006). No difference was observed between the positive and neutral conditions, *t*(59) = .40, *p* = .689, due to the presence of an interaction. This reflected a significant advantage in the recall of the positive information in the forward condition relative to the control condition (see Figure 1f). Specifically, in the forward condition, positive items were recalled better relative to the neutral ones as confirmed by a post-hoc Bonferroni-adjusted t test, *t*(19) = 3.13, *p* = .005, *d* = 0.98. Thus, aside from replicating the mnemonic time-travel effect with pictures, we found that, independent of this, forward motion facilitated the recall of positively valenced information.

8.1 General Discussion

In a series of six experiments, we demonstrated for the first time that motion-induced past-directed MTT significantly improved mnemonic performance for different types of information. The findings are robust (as confirmed by large effect sizes) and point at a stable effect which persists for at least 10 minutes after stimulus presentation. The effect was not disrupted by changes in experimental manipulation, or demographic and methodological differences. The findings were not confounded by the artificiality of walking backwards since the same advantage was observed with a video of a train journey viewed backwards (something often encountered in real life) and even when the walk was imagined. This is reinforced by the results of Experiment 5 in which forward imaginary motion produced an effect. Results of Experiment 6 indicated that the observed effect was not caused by the greater strength of backward relative to forward vection (Seno, Ito, Sunaga & Nakamura, 2010). Although we did not measure vection strength, the small visual angles employed in the study generally preclude the sensation of induced motion. Consequently, the results of Experiments 3 and 4 could be ascribed to the cognitive effects of optic flow. Neither motor on vestibular feedback nor the external motion cues were necessary—all that was needed was backward mental travel which brought individuals back to the moment of encoding and refreshed their memory trace. At the same time, increased realism of the task did positively affect recall of real-life scenes even though the results were generally stable in the face of methodological variation (e.g. free viewing vs. chin rest, 5 vs. 10 minutes distractor interval).

If we assume that the mnemonic record (at least for static items) is organized along the caudal portion of the subjective time line (Aksentijevic & Treider, 2016), backward motion helps the participant traverse the line and brings them back to the time of encoding, although we do not know the precise metric relationship between motion length/duration and temporal distance. Here, two (mutually not exclusive) possibilities exist. First, the mnemonic record is accessed directly—the backward journey in space-time renders encoded stimuli more salient. Another possibility is some form of context reinstatement—a mechanism used to explain the context-dependent memory effect (Dewhurst et al., 2009; Morris et al., 1977). The brevity of the distractor interval and constant environment mean that if any context reinstatement took place, this would have been mental—possibly based on cognitive and affective cues (Bramão, Karlsson & Johansson, 2017).

One useful way of conceptualizing the observed effect is in terms of temporally ordered long-term memory object files. Originally, the idea of such mnemonic units was postulated with regard to the memorized objects' spatial location (Hollingworth & Henderson, 2002). Since the current study controlled for spatial position of the stimuli (only partially in the case of the crime scene video), our results suggest some form of temporal indexing. In other words, files containing specific item-related information (including context) are ordered on the subjective time line and stored in a temporal sequence or a time-indexed spatial cluster (Figure 2a).

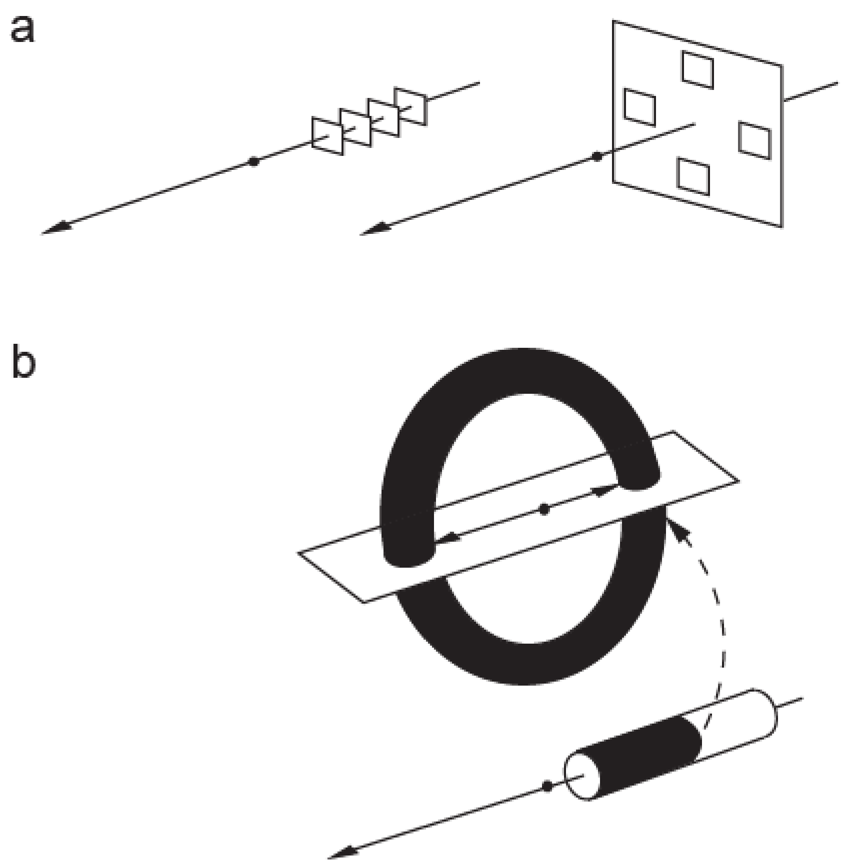

Figure 2. MTT for static and dynamic stimuli. (a) Discrete static stimuli are time-indexed on the mental time line either as a sequence or a cluster. (b) By contrast, hierarchically higher thematic "chunks" or event schemas of dynamic scenes (the black segment on the timeline) are stored in a way which makes them accessible to internally-generated MTT. In this case, a chunk is encoded as a closed loop at the higher processing stage enabling access to the information from both spatial directions. See text for details.

With regard to the crime scene video, there is evidence that perceived complex dynamic scenes contain a hierarchical structure consisting of a number of circumscribed units of meaning (event schemas) which comprise a number of component events (Zacks, Tversky & Iyer, 2001). Further, in addition to its temporal structure (sequence of events), the video possesses a spatial structure (a series of locations). These two types of information are eventually integrated into spatiotemporal "chunks" and such rich episodic binding of information is known to enhance hippocampal activation and subsequent memory (Davachi & Wagner, 2002). These chunks represent distinct units of action separated by salient "breakpoints" (points at which action and the overall tenor of the scene change; e.g. Newtson and Engquist, 1976) and have clear neural correlates (Zacks, Speer, Swallow & Maley, 2010). This could help explain the results of Experiment 5 where both forward and backward motion strongly improved recall relative to the control condition. Given the results of Experiment 6 (backward motion advantage for static image recall), this finding should be interpreted in terms of a special relationship between imaginary motion and the memory for dynamic scenes. It is possible that chunks of dynamic scenes are stored in topographically symmetrical arrangements such as closed loops (Bender & Beller, 2014) and that imaginary motion unconstrained by externally generated motion signals can access them irrespective of motion direction. (Figure 2b).

Finally, the finding that forward motion facilitated the recall of positively valenced pictures could reflect affective priming by forward movement (which is associated with concepts such as hope and progress) and could be related to the finding that upward motor action improves the retrieval of positive memories (Casasanto & Dijkstra, 2010; Seno, Kawabe, Ito, Sunaga, 2013). However, the absence of an interaction between the backward and neutral conditions suggested that backward motion was not associated with a negativity bias.

Importantly, our results support the close link between time, space and memory. In this sense, the observed effect taps into a multimodal cognitive domain which brings together thought, action, memory, movement, time and space. Further, our findings confirm one facet of Tulving's idea linking mental time travel and autonoetic consciousness, namely, that relating to the past. Tulving (1985) made the important temporal distinction between episodic memory (autonoetic consciousness, mentally re-experiencing an event as well as the ability to project oneself into a future scenario) and semantic memory (noetic consciousness, knowing without mental re-experience). According to this view, mental time travel is a property of the episodic memory system. It is worthwhile noting however that there is some evidence of a relationship between noetic consciousness and mental time travel (for a recent review see, Addis & Schacter, 2012) as well as arguments that it is the autonoetic component of episodic memory rather than this type of memory per se that is inherently linked with mental time travel (Klein, 2014).

The neural correlate of this effect most likely involves hippocampal structures responsible for encoding episodic trajectories that guide the participant back to the moment of encoding (Hasselmo, 2009). What about the future? Although a number of studies have demonstrated a significant overlap in the brain structures underpinning past and future time travel (Botzung, Dankova & Manning, 2008; Nyberg, Kim, Habib, Levine & Tulving, 2010), forward motion might have no discernible effects on memory because future thinking represents a separate mental domain (e.g. Atance & O'Neill, 2001) in spite of being based on episodic memory (Kwan, Carson, Addis & Rosenbaum, 2010). The act of constructing a future event lacks the episodic richness of "re-living" an event embedded in past memories—as confirmed by the evidence that future thinking contains less sensory imagery than past thinking (D'Argembeau & Van der Linden, 2004; Larsen, 1998) as well as the finding that different neural mechanisms underpin episodic recall and future thinking (Addis, Pan, Vu, Laiser & Schacter, 2009).

Looking at the results of the present study in totality, different types of motion (real, virtual, imaginary) and traversed distances (kilometres in Experiments 3 and 4 vs. meters in Experiments 1, 2, 5 and 6) produced similar effect sizes. This poses the question of a metric relationship between backward motion (if any) and the quality/quantity of recalled information. Although our experiments confirm the importance of past-directed MTT for memory, further research is needed to establish whether the effect is general (*any backward motion is effective*) or dependent on specific spatiotemporal parameters. Future research will also focus on importance of context by varying context cues at encoding and testing. We shall also explore the persistence of this “Mnemonic Time Travel Effect”, as well as the quality and the spatiotemporal structure of stored information. Finally, we shall examine whether or not it holds for other tests of episodic memory and the contribution of specific medial temporal lobe structures to eliciting this effect (Aggleton & Brown, 1999; Brandt, Eysenck, Kragh-Nielsen & von Oertzen, 2016; Diana, Yonelinas & Ranganath, 2007). Although the research is in its early stages, it shows a potential promise in terms of developing motion-based mnemonic aids which could prove especially helpful to the elderly and people with dementia. However, the implementation of such a procedure requires a better understanding of the relationship between the psychophysical parameters of mental time travel and resulting mnemonic gains.

In conclusion, we report for the first time a clear effect of motion-induced mental time travel on memory. Our results suggest that memory cannot be viewed in isolation from the rest of the cognitive system, or for that matter, the entirety of human experience. Rather than being an enclosed domain whose task it is to retain information and make it available, memory represents a component—albeit a very important one—of an embodied system which brings together perception, thinking and action. Hence, memory is dynamically and inextricably linked with experience of the present moment.

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Appendix 1: The memory questionnaire used in Experiments 1, 3 and 5

MNEMONIC TIME-TRAVEL EFFECT

Try to remember the details from the video. Carefully read each statement and circle the correct answer. <u>You have 3 minutes to complete the task.</u>

1. Was the woman in the video wearing gloves?	YES	NO
2. Her hair was	SHORT	LONG
3. The woman was a	BRUNETTE	BLONDE
4. The colour of the gate she came out of was	BLUE	GREEN
5. Her coat was	GREY	BROWN
6. Did the bench she sat on have a brass plate on it?	NO	YES
7. How many objects did she place on the bench?	TWO	THREE
8. Did she cross her legs?	YES	NO
9. The man who went past her came from her	RIGHT	LEFT
10. His jacket was	BLUE	BLACK
11. He was wearing a hoodie.	YES	NO
12. What was the woman doing when the "runner" approached her?	READING	OPENING A LUNCH BOX
13. Did the "runner's" track bottoms have a stripe?	NO	YES
14. The accomplice of the "runner" was the man who had walked across the path.	NO	YES
15. The person who took the purse was a	MAN	WOMAN
16. Their hair was	DARK	FAIR
17. Their shoes were	BLACK	BROWN
18. They had one hand in their pocket.	YES	NO
19. The person who offered their phone was the	RUNNER	ACCOMPLICE
20. Did the woman accept the offer?	YES	NO