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RESEARCH ARTICLE

The effect of ageing on multisensory integration for the control of movement timing

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Abstract Previously, it has been shown that synchronising actions with periodic pacing stimuli are unaffected by ageing. However, synchronisation often requires combining evidence across multiple sources of timing information. We have previously shown the brain integrates multisensory cues to achieve a best estimate of the events in time and subsequently reduces variability in synchronised movements (Elliott et al. in Eur J Neurosci 31(10):1828–1835, 2010). Yet, it is unclear if sensory integration of temporal cues in older adults is degraded and whether this leads to reduced synchronisation performance. Here, we test for age-related changes when synchronising actions to multisensory temporal cues. We compared synchronisation performance between young ($N = 15$, aged 18–37 years) and older adults ($N = 15$, aged 63–80 years) using a finger-tapping task to auditory and tactile metronomes presented unimodally and bimodally. We added temporal jitter to the auditory metronome to determine whether participants would integrate auditory and tactile signals, with reduced weighting of the auditory metronome as its reliability decreased under bimodal conditions. We found that older adults matched the performance of young adults when synchronising to an isochronous auditory or tactile metronome. When the temporal regularity of the auditory metronome was reduced, older adults' performance was degraded to a greater extent than the young adults in both unimodal and bimodal conditions. However, proportionally both groups showed similar improvements in synchronisation performance in bimodal conditions compared with the equivalent, auditory-only conditions. We conclude that while older adults become more variable in synchronising to less regular beats, they do not show any deficit in the integration of multisensory temporal cues, suggesting that using multisensory information may help mitigate any deficits in coordinating actions to complex timing cues.

Keywords Movement synchronisation · Multisensory integration · Ageing · Temporal action

Introduction

Making movements in synchrony to a stream of events requires accurate time keeping to (1) anticipate the onset of the next event and (2) to make movement adjustments that correct for timing errors between the events and motor actions. The ability to make these synchronised movements is fundamental for everyday events such as avoiding obstacles or interacting with another person. Recently, we have shown that synchronisation accuracy is improved if the timing information about the events is available across multiple sensory modalities (Elliott et al. 2010; Wing et al. 2010). Here, we investigate whether improved movement synchronisation performance from multisensory integration is robust to neurological and physiological consequences of the ageing process.

Work investigating movement synchronisation has tended to use a paradigm where participants tap their finger in time to a regular beat. In the simplest form of the task, humans are able to make repetitive timed movements without external timing cues, based on an internal timekeeper (Wing and Kristofferson 1973). The Wing–Kristofferson model showed that the timekeeping and resultant motor processes produce independent sources of error, resulting in

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the temporal variability observed in the intervals between finger tap movements (Wing and Kristofferson 1973). An extension of this task is to synchronise finger tap movements to an external pacing source (i.e. a metronome, typically presented as a stream of auditory clicks or beeps). The timing error is quantified by the asynchrony—the difference between the onset of the metronome beat and the onset of the finger tap. Synchronisation accuracy is then quantified as the mean of the asynchronies across a trial, while the standard deviation of the asynchronies provides a measure of variability of the synchronised movements. This movement synchronisation task can be described accurately by a linear phase correction model (Vorberg and Schulze 2002; Vorberg and Wing 1996) and can be used to estimate the statistics of the temporal corrections made on each subsequent finger tap based on the previous asynchrony. This error correction process has been observed for both upper (Elliott et al. 2009a; Repp 2001; Turgeon et al. 2011) and lower limb (Chen et al. 2006; Pelton et al. 2010; Roerdink et al. 2009) movements. Statistical analysis of the linear phase correction model suggests that the correction strategy used in synchronising is optimal in the sense of minimising the asynchrony variability (Vorberg and Schulze 2002).

Being able to accurately time and synchronise actions is essential for maintaining stability in movement, reacting to unexpected events and interacting with others. Hence, an important area of investigation is how movement timing performance changes over the lifespan. For tasks where participants hear an isochronous beat for a short period of time and then continue moving at the same tempo, no difference in timing variability has been found between young and old adults (Krampe et al. 2001). Similarly, in a synchronisation task requiring participants to keep finger-tapping movements in time with an isochronous metronome beat, asynchrony variability was not degraded in old age (Drewing et al. 2006). More recently, differences in the error correction processes between young and old adults have been investigated using a phase perturbed metronome paradigm (Turgeon et al. 2011). By randomly lengthening or shortening a single interval between beats in an otherwise isochronous metronome, it is possible to measure the phase correction performance to that perturbation (i.e. how quickly participants correct the timing error caused by the perturbed interval). Turgeon and colleagues found no difference in the speed of correction detected between young and older adults, suggesting that timing error processing remains intact in older age. In contrast, however, there are known to be substantial timing performance differences between older adults and young adults in the production or synchronisation to non-isochronous sequences of intervals. These tasks require participants to tap sequences of irregular intervals forming complex rhythms. Older adults exhibit significantly greater variability in the timing of movements compared to young adults (Krampe et al. 2001, 2005), considered to be a consequence of the sequencing demanding greater attentional resources in older age.

An isochronous stream of events presented in a single modality (as used by the majority of movement synchronisation studies) represents the simplest form of synchronisation task where the next event is fully predictable. In reality, there is often a degree of uncertainty as to the occurrence of the next event caused by noise—either external or inherent to sampling by the sensory system. Here, we examine how participants correct to continuously perturbed (or ‘jittered’, Elliott et al. 2010) metronome beats—i.e. an isochronous metronome that is corrupted by noise such that there is a level of uncertainty to the onset of every beat. We expected older adults to perform worse at this task compared with young adults, due to the irregular sequence intervals created by the jittered metronome being more similar to the complex rhythms used by Krampe et al. (2001, 2005), than the regular beats used in other studies.

The brain reduces the uncertainty of events (or objects) perceived by combining information across multiple modalities (Alais and Burr 2004; van Beers et al. 1999; Ernst and Banks 2002). These multiple sources of information are combined to define a single perceived event which, if each source is weighted accordingly, will reduce the overall uncertainty to give an optimal estimate of the true event (Alais and Burr 2004; van Beers et al. 1999; Ernst and Banks 2002). In our earlier studies, we found this was also true for the integration of multisensory timing information (Elliott et al. 2010; Wing et al. 2010). Young adults were found to combine bimodal pairs of auditory, visual or tactile metronome, in a quasi-optimal fashion, reducing the asynchrony variability when synchronising movements. In older adults, a reduced ability to appropriately integrate cues across modalities could be a significant contributor to the prevalence of falls (van Hedel and Dietz 2004; Jeka et al. 2010; Setti et al. 2011). In particular, it is thought that older adult fallers are both slow to reweight and do not correctly weight their reliance on visual, proprioceptive and vestibular sensory information, causing postural instability if a sudden perturbation occurs within those modalities (Allison et al. 2006; Jeka et al. 2010; Teasdale and Simoneau 2001). Maintaining stability in walking relies not only on balance but importantly the timing of movements as well. Specifically, individuals must rapidly correct movements in response to events or obstacles that occur unexpectedly. Here, we examine whether this process can be enhanced in older participants through the integration of multisensory cues. In particular, does the multisensory enhancement observed in younger adults persist in old age?

In the present study, we examine the difference in movement timing performance between young and old adults when synchronising finger movements to unimodal (auditory or tactile) or bimodal (simultaneous auditory and tactile) metronomes. We jittered the auditory metronome to increase the uncertainty in the intervals between beats, while the tactile modality remained isochronous. As in our previous work, we expected participants to integrate cues, changing the weighting between modalities as they differed in reliability to extract the best estimate of the underlying (isochronous) beat. Based on previous findings, we expected that older adults would be more variable in unimodal conditions to highly irregular metronomes and would also show a reduced effects of integration when the metronome beats were presented bimodally.

Materials and methods

Two groups of participants were used: young adults and older adults. Older adults ($N = 15$, all right-handed, 5 male, aged 63–80 years, mean 72.6 years) were recruited from the local community by advertising in the local print media. They were screened to ensure that they had no history of neurological disorders. Young adults ($N = 15$, 11 right-handed, 9 male, aged 18–37 years, mean 27.7 years) were recruited from staff and students at the University of Birmingham. All participants provided informed consent and were screened for sensory and motor deficits. In addition, participants in the older adult group completed a Mini Mental State Examination (Folstein et al. 1975) to screen for cognitive impairment before beginning the experiment. One participant scored 25, while the remainder scored 28 or above. Scores of 25 or above (out of 30) indicate no deficit in cognitive ability. We further questioned participants about their musical ability, with 6 older and 3 young adults having recently played a musical instrument.

Participants were presented with a metronome (inter-onset interval (IOI), 500 ms) in different sensory modalities: either auditory (a beep emitted from a piezo-electric auditory buzzer) or tactile (a tap on the non-dominant index finger delivered by a solenoid-based tactile actuator—MSTC3, M and E Solve, UK). The metronomes were presented either unimodally (auditory only or tactile only) or bimodally (auditory and tactile simultaneously). Participants were instructed to tap the index finger of their dominant hand on a force sensitive resistor in time to the metronome. Practice trials were given which demonstrated the conditions and modalities under which the metronome would be presented. Further practice trials were given until both the experimenter and participant were confident the experiment could be completed successfully. Participants were instructed to pay attention to all available cues during the trials. Each trial consisted of 30 metronome beats and participants completed 7 trials for each of thirteen conditions (see Table 1). The order of condition presentation was blocked and randomised across participants. The experiment took approximately 1 h to complete and participants took regular breaks over the course of the experiment.

Table 1 Thirteen conditions were tested in total, by applying three levels of jitter to the auditory metronome and three levels of phase offset in multimodal conditions

Conditions	Modality	Jitter[a] (SD, ms)	Phase offset (ms)
1–3	Auditory	0, 30, 60	
4	Tactile	0	
5–13	Auditory–tactile	0, 30, 60	0, 40, 80

[a] Applied to auditory modalities only

Responses were registered using a data acquisition device (USB-6229, National Instruments Inc., USA). Metronome presentation was controlled using the MatTAP toolbox (Elliott et al. 2009b) in MATLAB (version 2009a; The Mathworks Inc., MA, USA). To suppress any auditory feedback from the tactile actuator and their own finger tap responses, participants wore headphones playing white noise.

To manipulate the perceived difference in temporal reliability between the auditory and tactile modalities, we 'jittered' the auditory metronome by adding a random temporal perturbation taken from a Gaussian distribution, $N(0, \sigma)$, to the regular onset time of each metronome beat (Fig. 1; Elliott et al. 2010; Wing et al. 2010). The perturbations applied to each metronome event were independent and referenced to the time at which the regular beat occurred, i.e. overall phase was unaffected, with the mean interval of the jittered metronome remaining (approximately) equal to that of the underlying, regular metronome. Increasing the standard deviation of the distribution, σ, from which the perturbation value was sampled, resulted in a more variable metronome and hence reduced the temporal regularity. We used three jitter conditions, with standard deviations of 0, 30 and 60 ms. The tactile metronome remained reliable across all conditions (0 ms jitter). We wanted to test whether participants would integrate the two modalities to infer a best estimate of the underlying, regular beat. As such, in bimodal presentations, we expected to see participants rely more on the tactile metronome as the temporal irregularity of the auditory metronome increased.

We made an additional manipulation to the metronomes by varying the phase offset between the auditory and tactile signals. In particular, the two metronomes could be in phase ($\phi = 0$ ms) or differ in phase by an average of 40 or 80 ms ($\phi = \{-40, -80\}$ ms; Fig. 1). Phase offset values represented the offset of the auditory metronome beats with respect to tactile, with negative values indicating that the auditory cues preceded tactile (pilot testing had indi-

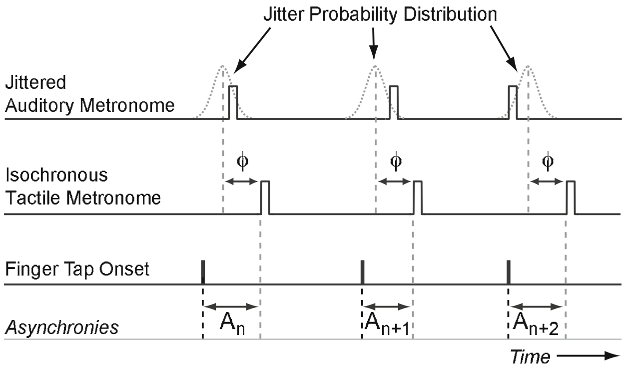

Fig. 1 An illustration showing the timing relationships between the two metronomes in bimodal conditions and the calculation of asynchronies in the corresponding finger tap onsets (i.e. when the finger makes contact with the surface). The square wave pulses represent the metronome beats. Both metronomes had the same underlying period of 500 ms. To create temporal uncertainty, jitter was added to the auditory metronome (note irregular beat onsets), i.e., a random perturbation value, taken from a Gaussian distribution, was added to the regular onset time of each beat. The standard deviation of the distribution was varied (0, 30 or 60 ms) to set the level of uncertainty. The auditory metronome was also phase offset (ϕ) relative to the tactile metronome, leading by $\phi = 0, -40$ or -80 ms. Asynchronies (A) were calculated between the tap onsets and the onset of the tactile metronome. In conditions where only the auditory metronome was presented, asynchronies were measured to the underlying isochronous beat (i.e. the onset prior to jitter being applied)

cated no effect of order). The jitter manipulation described previously was added to the phase-shifted auditory beats, allowing us to investigate both the effects of temporal uncertainty and the phase offset between the multisensory cues.

Results were analysed in terms of mean asynchrony and the mean, standard deviation of asynchronies across conditions, which were extracted and analysed using the MatTAP Toolbox (Elliott et al. 2009b). Asynchronies were measured with respect to the tactile metronome in tactile-only and audio-tactile conditions, or the underlying un-jittered metronome beats in auditory-only conditions. All additional analyses were performed using MATLAB. Mixed ANOVA statistical analyses were completed in SPSS (v16.0; SPSS Inc., IL, USA), with age group as the between-subjects factor and jitter and phase offset as the within-subjects factors, where appropriate. Greenhouse–Geisser corrections were made for sphericity violations where necessary.

Results

We tested for differences in multisensory integration between young and older adults, analysing synchronisation performance in terms of asynchrony variability (standard deviation, SD) and mean asynchrony within a trial. We then took the mean of these measures across trials (within each condition) and then across participants. We first examine the effects of regular (auditory and tactile) and jittered (auditory) unimodal metronomes on the asynchrony SD in young and older groups. Second, we test for a reduction in asynchrony SD when the metronome is presented bimodally (auditory and tactile simultaneously), again testing for differences between young and older groups and examining the effects of jitter. Finally, we examine how adding a phase offset between modalities influences asynchrony SD and the mean asynchrony in young and older adult groups.

Manipulating the regularity and modality of the metronomes had a direct impact on the synchronisation performance of participants across both young and older groups. Applying increasing temporal jitter to the auditory metronome led to increases in the asynchrony SD of both groups ($F_{1.4,39.8} = 222.58$, $P < .001$; Fig. 2a). On the other hand, both groups demonstrated a clear advantage of synchronising to multimodal cues, with asynchrony variability reduced when the metronome consisted of simultaneous auditory and tactile beats compared to the equivalent auditory-only conditions ($F_{2,56} = 18.48$, $P < .001$; Fig. 2a).

Asynchrony variability to jittered, unimodal metronomes

Overall, asynchrony variability differed between age groups ($F_{1,28} = 11.21$, $P = .002$), with older adults showing higher variability than the young adult group. In particular, we found that older adults were affected more by increasingly unreliable metronomes than the young group, with a greater rate of increase in asynchrony variability as the jitter applied to the metronome was increased ($F_{1.4,39.8} = 10.97$, $P = .001$). The results showed no difference in asynchrony variability between young and older groups when either auditory or tactile metronomes were isochronous ($F_{1,28} = 1.58$, $P = .219$). This indicates that there is little underlying difference in motor variability for tapping or sensory registration of the metronome cues between the young and older groups. However, the increasing difference between groups as the jitter increases shows that the more complex, or uncertain, metronome beats impacted on the variability of the older group. We considered that this could be due to older adults making corrections that were more strongly correlated with the irregular auditory cues. We tested for this by measuring the correction coefficient (proportional to the lag 1 cross-covariance between a participant's tap intervals and corresponding metronome intervals; (Vorberg and Schulze 2002; Vorberg and Wing 1996) in the high jitter (60 ms), auditory-only condition. We found that both groups had near identical correction coefficients (young: .58 ± .32; older: .54 ± .21) discounting the likelihood that the older group was making stronger

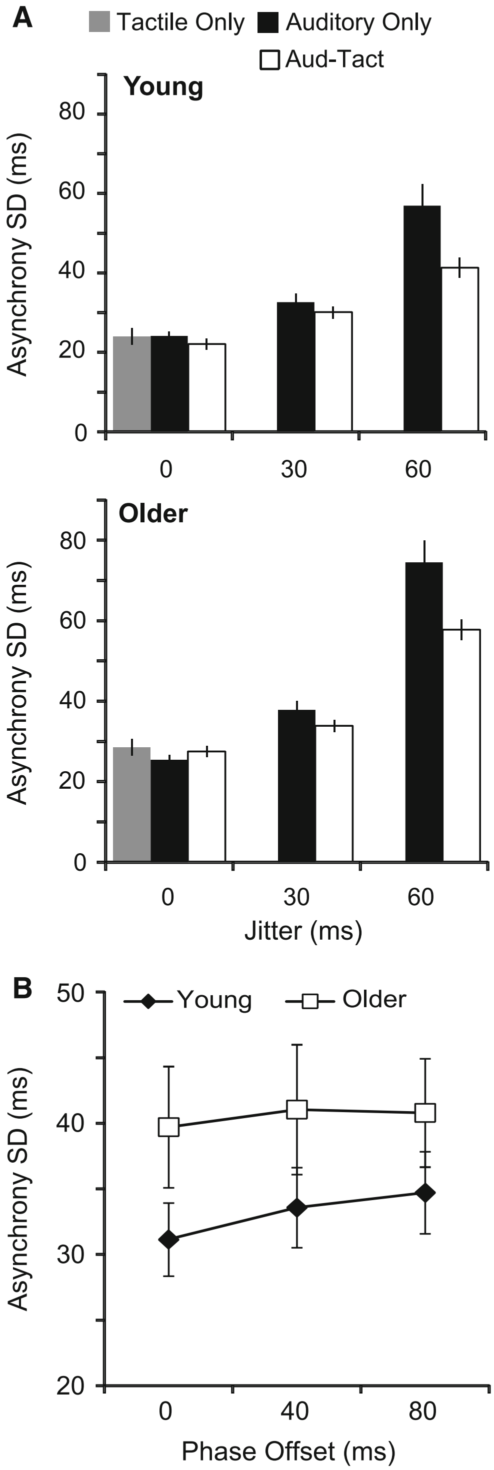

Fig. 2 **a** Comparison of variability (standard deviation, *SD*) in asynchronies for unimodal and bimodal conditions. The asynchrony SD in the audio-tactile conditions (with no phase offset, *white bars*) is compared with the auditory-only (*black*) and tactile-only (*grey*) results for each jitter condition. Separate plots are shown for each group. *Error bars* represent standard error. **b** Asynchrony variability as a function of the phase offset between modality. Asynchrony SD is plotted against the phase offset in bimodal conditions. Values are averaged over jitter conditions and separated into young adult (*filled diamond*) and older adult (*open square*) groups. *Error bars* represent standard error

corrections to the noisy metronome cues than the younger group.

Effect of multimodal cues on asynchrony variability

Older adults showed a proportionally similar benefit to multimodal cues as young adults, with no significant difference between reductions in variability across any jitter conditions ($F_{2,56} < 1$, $P = .610$). This multisensory advantage increased with increasing jitter on the auditory metronome ($F_{1.2,34.4} = 15.70$, $P < .001$), suggesting participants placed greater reliance on the tactile metronome as the auditory cues became increasingly uncertain. Hence, despite being proportionally more variable overall (in jittered conditions), older adults demonstrate a similar reduction in variability due to multimodal cues as the young adult group.

Effect of phase separation between multimodal cues

We further examined the effect of phase separation between the beats from the two modalities on both the asynchrony variability and mean asynchrony. The central nervous system (CNS) must infer the relevance of multisensory cues (Körding et al. 2007; Sato et al. 2007)—should they be integrated into a common event or treated independently? We expected that increasing the phase offsets between the two modalities would reduce the likelihood of participants integrating the cues, instead treating them as independent events. If this were the case, then bimodal conditions were expected to show increased variability as the phase offset increased. Overall, across groups, we observed a small increase in asynchrony variability with increasing phase offset ($F_{2,56} = 3.52$, $P = .036$; Fig. 2b). This suggests that there is some reduction in integration due to the phase offset, but as the increases are small, it appears participants are consistent in targeting a specific modality, rather than 'switching' between modalities within a trial. We found no difference in the effect of phase offset between older and young groups ($F_{2,56} < 1$, $P = .411$). Further, there was no additional effect on asynchrony variability when increasing jitter was applied to the auditory metronome while also increasing the phase offset between modalities ($F_{2,56} < 1$, $P = .438$).

Effect of phase offset on mean asynchrony

Increasing phase offset between the auditory and tactile beats was found to strongly influence the mean asynchrony in both young and older groups, but jitter had no additional effect on the influence of phase offset (Fig. 3). Typically, participants will tap in anticipation of the beat when synchronising to auditory metronomes, resulting in negative

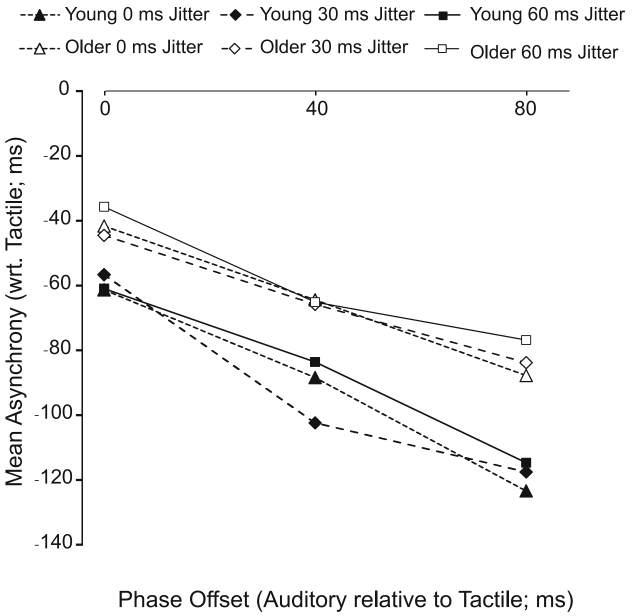

Fig. 3 Mean asynchrony versus phase offset. The group mean asynchronies with respect to the tactile metronome beats are plotted against the phase offset of the auditory metronome relative to tactile. Phase offset represents the time interval between the onsets of the tactile metronome beats and the preceding auditory beats precede the tactile beats. *Lines* are plotted for each jitter condition and separated into young adult (*filled markers*) and older adult (*open markers*) groups. *Error bars* not shown for clarity (no significant differences between older and younger groups were found for the gradient or intercepts)

asynchronies of around 50–100 ms (for a 500 ms IOI). Here, by changing the phase offset between modalities, we were able to observe how a multisensory metronome affected the tapping asynchronies and in particular, how the metronome beats were targeted when the multimodal cues, with slightly differing temporal onsets, were integrated. As with the variability analyses, we expected participants to weight cues according to their relative reliabilities (which we manipulated by applying jitter). Hence, we expected that the mean asynchrony (measured relative to the tactile beats) would become more negative as the auditory beats increasingly preceded the tactile beat, but the different levels of jitter would alter the strength of this effect. That is, when the auditory metronome had a high temporal uncertainty, the mean asynchrony would be less affected by phase offset due to a stronger weighting to the tactile metronome. We measured the mean asynchrony for each phase offset and jitter condition and averaged across participants for the young and older groups (Fig. 3). Both groups showed a strong influence of phase offset on the mean asynchrony ($F_{1.5,42.8} = 98.93$, $P < .001$). However, in contrast to our predictions, there was no difference in the influence of phase offset for increasing levels of jitter applied to the auditory metronome ($F_{4,112} = 1.57$, $P = .188$; Fig. 3). Thus, while it is clear that both groups integrate the two modalities to reduce variability, the temporal events to which finger taps are targeted during synchronisation remain independent of any weighting due to temporal uncertainty.

Effects of age on mean asynchrony

The group means indicated that older adults tended to have a smaller negative asynchrony than the young adults (Fig. 3). Collapsing over jitter conditions, we tested whether age had an effect on the size of the negative asynchronies observed, possibly due to changes in processing time intervals (Vanneste et al. 2001) or longer feedback delays (Aschersleben and Prinz 1995; Aschersleben et al. 2001; Stenneken et al. 2006). Furthermore, we tested if there was an age-related effect on the mean asynchrony due to the phase offset between modalities, potentially caused by differences in weighting between modalities. Least-squares linear regression lines were fitted to each participant's mean asynchronies against phase offset, collapsed over jitter. The gradient of the regression lines was representative of the weighting given to the two modalities. The intercept indicated the expected mean asynchrony to an auditory-tactile metronome with zero phase offset. We compared the gradient and intercept values between young and older groups. There was a slightly higher gradient for the younger group (young: .74, older: .53), but this was found to be not significant due to individual differences ($F_{1,28} = 3.46$, $P = .073$). As the gradient was only just insignificant, we analysed the data further to check for any consistent differences between the young and older groups, by running a k-means clustering algorithm on the data. Using a bootstrap approach to run the cluster algorithm 5,000 times on the sampled data, we found no evidence of consistent differences in gradient between the young and older groups. Similarly, we found no significant difference was found between young and older adults in the intercept (young: −60.4 ms, older: −41.8 ms; $F_{1,28} = 2.17$, $P = .152$).

Discussion

We have compared the synchronisation accuracy of older and younger adults when performing a finger-tapping task to metronome beats presented as auditory tones, tactile taps or in both auditory and tactile modalities presented together. Our aim was to investigate whether there are changes in old age in the integration of multisensory temporal events and if so, how this affects movement timing. We used temporal jitter added to the auditory metronome in both unimodal and bimodal conditions to test for age-related differences in synchronisation performance to irregular metronome beats. Using jitter and increasing phase offset between cues in multimodal conditions also allowed us to examine any changes in weighting between modalities. As the jitter increased, we tested to see if participants changed their weighting towards the more reliable tactile metronome and, hence, were able to get a near-optimal estimate of the temporal events defining the metronome intervals (Elliott et al. 2010; Wing et al. 2010).

The baseline, unimodal conditions provided useful insights into the general performance similarities between the young and older groups. In particular, we have shown that there was no age-related difference in variability when tapping to either auditory or tactile isochronous metronomes. The results indicate that the sensory registration of discrete auditory and tactile temporal cues appear to remain, on the whole, unaffected in older age (at least within the supra-threshold bounds within which we have tested). Furthermore, the near equal measures of asynchrony variability in these conditions indicate that motor function and the ability to maintain a simple isochronous beat has not deteriorated in our group of healthy older adults. This finding corroborates previous work showing that older adults show little difference compared with younger adults synchronising movements to regular auditory metronomes (Drewing et al. 2006; Krampe et al. 2005; Turgeon et al. 2011; Vanneste et al. 2001).

In contrast, we found differences between young and older adults in conditions where the metronome was jittered. Initially, we thought this was due to older adults showing a stronger correction to the jittered auditory beats. We tested this through measures of lag 1 cross-covariance between the tap intervals and the jittered metronome intervals, finding that contrary to our prediction, young and older adults showed similar levels of correction. Hence, the extra variance exhibited by the older group is likely to be due to the processing of irregular timing intervals. In particular, there is strong evidence that the sequencing of complex movements becomes more difficult in old age (Fraser et al. 2010), suggesting executive control degrades with age. Moreover, tapping to complex rhythms is more variable in older adults than young (Krampe et al. 2005), suggesting executive control is required for synchronisation to rhythmic but not isochronous cues. It is possible that in this task the irregular beats from the jitter engages the same executive control processes as complex rhythmic sequences, giving rise to greater variability in older adults than younger adults only in the jittered conditions. This finding could have important consequences for stability in walking in older age. Specifically, while walking is an almost automatic process in young adults, increased cognitive resources are thought to be required to maintain stability while walking in older adults (Beauchet et al. 2009; Yogev et al. 2005, 2008). Hence, the manipulation of uncertainty in the sensory information used to time step movements could be used to examine and quantify the attentional demands of walking in older participants.

Under bimodal conditions, we observed that older adults showed the same multisensory advantage as younger adults. This finding indicates that the integration of multisensory temporal cues remains intact in older age, with the same proportion of improvement in synchronisation accuracy shown in both groups. For both groups, we saw the biggest reduction in asynchrony variability in the condition where the jitter on the auditory metronome was highest. This indicates that participants increased their reliance on the tactile beats as the auditory beats became more irregular. However, as noted in our previous study (Elliott et al. 2010), high levels of jitter also had an effect of reducing the optimality of the multisensory integration.

While we found that mean asynchronies were influenced by phase offset, there was no change in mean asynchrony produced by increasing jitter on the auditory metronome. This is somewhat surprising as a maximum likelihood model of integration would suggest that the estimated metronome beat should shift closer to the more reliable signal (Alais and Burr 2004; Ernst and Banks 2002). We therefore expected that increasing the phase offset between auditory and tactile beats would lead to asynchronies (measured relative to the tactile beats) becoming more negative as the auditory beats increasingly preceded the tactile. In addition, we expected that by manipulating the reliability of the auditory metronome (using jitter), we would alter the strength of the change in mean asynchrony. Surprisingly, we found that jitter had no influence on the change in asynchrony as the phase offset increased, with consistent results across all three jitter conditions. This is in contradiction to the multisensory perception studies showing that the ‘location’ of an object is determined by the maximum likelihood weighted sum (e.g. Alais and Burr 2004). In this sensorimotor synchronisation task, it is likely that more factors are influencing the targeting of movements in time compared to a pure perceptual judgement task. For example, the common observation of negative asynchronies is suggested to be due to feedback delay differences between modalities (Aschersleben and Prinz 1995; Stenneken et al. 2006). The relatively large differences in baseline mean asynchronies between participants and the lack of any consistent differences between age groups suggest that these factors vary greatly between individuals. This may have masked the weighting effects that we have otherwise observed from the reduction in synchronisation variability in the multimodal conditions.

In summary, we have shown that the ability to integrate multisensory, temporal information remains in older adults and improves the accuracy of synchronised actions. We have further demonstrated that, for randomly jittered auditory metronome intervals, synchronisation variability increases more in older compared to young adults, likely due to the need for increased attention and higher level executive control to maintain phase with the varying beat intervals. Our results highlight the potential of multisensory devices being used as possible aids to older adults for enhancing movement timing performance (e.g. in walking). Certainly, it appears that the availability of multisensory information can counteract the increased movement variability we observed in older adults when synchronising to high uncertainty, unimodal temporal events.

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