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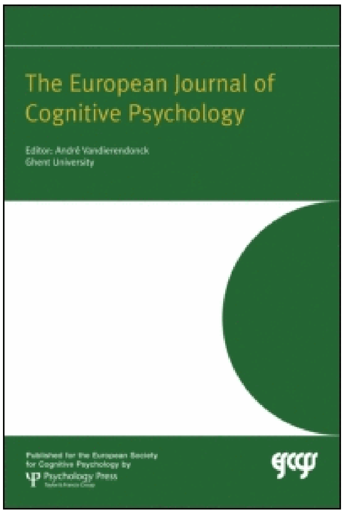

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The effects of age and task domain on dual task performance: A meta-analysis

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The effects of age and task domain on dual task performance: A meta-analysis

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Recent research has provided mixed findings as to whether older adults find dual tasking problematic. Here, we examined whether methodological variations across studies can account for the discrepancies in the literature. Meta-analyses conducted on the results of 34 studies conducted between 1981 and 2003 found a strong overall effect size (d = .68), which indicated a clear age-related dual tasking impairment. However, this effect size was not representative of all the individual studies reported. Subsequent analyses, using an analysis of variance analogue (Hedges & Olkin, 1985), investigated potential moderators responsible for the variability in the effect sizes across studies. These secondary analyses included a comparison of dependent measure used, whether baseline differences in performance had been controlled for, and task domain. Task domain was found to be the critical moderator variable. Notably, tasks with a substantial controlled processing, or motor component showed greater dual task impairment than tasks that were relatively simple or relied on automatic processing.

A great deal of research has been conducted on the effect of age on dual task performance, both in the laboratory, and in everyday activities such as driving and working in complex environments in the work place (McDowd, Vercruyssen, & Birren, 1991). Whilst this literature has supported the idea that older adults have difficulty when required to combine two activities, it has proved difficult to draw firm conclusions about this literature because of the diversity of methods used. So, although older adults seem generally impaired when combining two tasks, there is debate as to whether this impairment holds when

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baseline performance on a single task is taken into account (e.g., Somberg & Salthouse, 1982). Nor is it yet clear whether the magnitude of the observed age-deficits in dual tasking are systematically related to methodological differences across studies. This is due, in part, to the wide diversity of tasks used, either singly, or in combination. To address these issues, we report meta-analyses aimed at summarising the behavioural evidence to date. In particular, analyses are carried out to determine which task variables are critical in moderating the age effect in dual tasking.

Methodological variation across studies is often cited as a critical factor explaining why age differences in dual task performance are only found under certain conditions (see de Ribaupierre & Ludwig, 2003; Somberg & Salthouse, 1982; Salthouse, Fristoe, Lineweaver, & Coon, 1995). To be clear, we believe this is the primary reason for the variable research findings in the literature. For example, there is no agreement on the most suitable metric for measuring dual task performance. Typically, older adults are found to be poorer at dual tasking on the component tasks when absolute measures of performance are used but this is hardly surprising since they are poor on a large number of tasks when they are performed alone. This consideration led Somberg and Salthouse (1982) to advocate the use of proportionate dual task cost ([dual–single]/single) rather than absolute differences (dual–single) in performance. In fact, they concluded that when such an index is employed, age differences in dual task performance (as indexed by primary and secondary task performance) are removed and so the observed dual task impairment is the result of single task baseline differences in performance. However, Guttentag (1989) argued that both the use of absolute and proportionate difference scores are legitimate, although the use of proportional changes in performance provide a more conservative estimate of dual task costs, and so any observed age differences are more likely to reflect a genuine age-related impairment. Metric selection and the problem of baseline differences in performance have been addressed by manipulating task parameters to equate single task performance on the primary and secondary tasks. This method must be used with care because if the task parameters are altered to equate performance it could be argued that age comparisons are unreliable as the nature of the task has changed. In the present meta-analysis we contrast those studies that do, and do not, control for baseline differences in single task performance. In addition, we explore whether the nature of this control is critical in moderating the magnitude of the dual task effect, by contrasting the use of the proportionate cost measure advocated by Somberg and Salthouse with the use of matching procedures.

The task domain and/or task combination is another influential factor with regards to whether an age effect is observed in dual tasking studies. For instance, two studies that used very similar procedures found an age effect when memory tasks were used (Salthouse, Rogan, & Prill, 1984) and age invariance when two perceptual tasks were performed together (Somberg & Salthouse, 1982). From this, Salthouse et al. (1995) argued that what is needed is a thorough investigation of the impact of specific tasks and combinations on age differences in dual task performance. Similarly, Tun and Wingfield (1993) argue that dual task performance decrements appear to be dependent on the specific tasks involved. In that paper a review of the language processing domain indicated age equivalence in dual task performance. Importantly, the authors suggest a deficit in executive control may be responsible for impaired dual tasking in old age. When performing concurrent activities it is necessary to develop strategies to effectively schedule and coordinate task demands. Indeed, a wide body of evidence points to an executive deficit in old age but why is impairment seen only in some dual tasks? The authors concluded that when tasks are relatively automatic or data driven, performance might be resilient to concurrent task demands even for older adults, as there is less need for executive processing mechanisms.

Particularly relevant here is a study carried out by Riby, Perfect, and Stollery (2004). In that study, participants were required to perform both semantic and episodic dual tasks. Age differences in dual task performance were only observed in the episodic dual tasks. Significantly, the pattern of age effects remained the same when the difficulties of the dual tasks were manipulated. Riby et al. suggest there is less need to employ strategic or controlled processes to manage concurrent tasks in domains of cognition relatively intact in ageing (e.g., semantic memory). In similar vein, the impact of poor cognitive control on dual task performance has been observed in the sensorimotor domain. Lindenberger, Marsiske, and Baltes (2000) report that, with increasing years, controlled/executive processes are in high demand to compensate for declines in sensorimotor performance. Consequently, competing activities are more detrimental for older adults in this domain.

The suggestion of domain specific effects in dual tasking is consistent with general models of ageing distinguishing between greater slowing for central compared to peripheral processing (e.g., Cerella, 1985). Therefore, it is perhaps predictable that there is variability in dual task costs across processing domains. Similarly, distinctions have been made between, lexical and nonlexical tasks (e.g., Lima, Hale, & Myerson, 1991), direct versus indirect memory tasks (e.g., Light, 1991), and between automatic and controlled tasks (e.g., Jennings & Jacoby, 1993). Based on these processing domain distinctions we could partition and compare dual tasks in a number of ways, but to make our investigations more manageable we focus on possible age difference in dual task performance in the cognitive (‘‘controlled’’ versus ‘‘automatic’’ tasks) and motor domains.

META-ANALYSIS

A meta-analysis is a statistical procedure used to combine the results of several independent studies. Glass (1976, p. 3) defined meta-analysis as ‘‘an analysis of analyses’’, ideal for investigating the magnitude of a treatment effect across studies. The procedures enable a summary of research findings by extracting a common metric such as the effect size. There are many effect size metrics that can be employed (e.g., the standardised difference between two means—*d* and the Pearson product moment correlation coefficient *r*). However, all metrics represent some standardised form of the treatment effect. Subsequent investigations can then address whether differences in study characteristics or sampling error are responsible for variations in effect size across studies. Since there have been a large number of studies on age differences in dual task performance, sometimes giving conflicting results, carrying out a meta-analysis is highly desirable. Specifically, study characteristics can be examined to uncover moderator variables of the variation in effect size, which can assist in generating hypotheses for future experimental work.

Kieley (1991, in Hartley, 1992) was the first to carry out a meta-analysis on age differences in dual task performance, finding a large average effect size of $d = .99$. The effect size *d*[1] refers to the most commonly used effect size estimator and represents the standardised difference between the control and experimental groups' performance, $d = (\text{Mean}_e–\text{Mean}_c)/SD$. Hedges and Olkin (1985) described effect sizes of .2, .5, and .8 as small, medium, and large, respectively. Kieley reported a large overall effect size but the individual effect sizes were not homogeneous, which implies different factors determining the effect. To investigate this further, dichotic listening tests were eliminated from the analysis as it could be argued that such tasks are not dual tasks in the strictest sense. Studies were also subdivided according to study characteristics and tested for homogeneity within each subgroup. The studies were grouped based on such factors as whether baseline differences in performance had been considered, difficulty or modality of the tasks, and the dependent measure used. Although the individual studies and effect sizes were reported no exact details were given of the subgroups analysed. However, Hartley argued that there was some suggestion that older adults are particularly disadvantaged at dual tasking when the tasks are difficult or when there is a substantial memory or motor component.

Chen (2000) carried out similar investigations on 25 studies between 1981 and 1997. This author found an overall effect size that was significantly greater than zero ($g = .79$). Studies were then divided according to whether proportionate or absolute measures of performance had been used. It was found that the effect size for the studies reporting the proportionate measures of performance were greater than that of those reporting the absolute measures of performance ($g = 1.18$ and $g = .51$, respectively). This was somewhat surprising, as one would expect those studies that did not control for baseline differences in performance to report larger age effects. A separate analysis was carried out on the reaction

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[1] *d* is often referred to as *g*. However, see Hedges and Olkin (1985) for distinction between adjusted (*d*) and unadjusted (*g*) effect size estimates.

time and accuracy data. The greatest effects were found for those studies using reaction time as a dependent variable. The final finding related to whether tasks shared the same input modality, output modality or the same internal codes of processing. It was found that the age effect was the greatest in those tasks that shared the same internal codes of processing (i.e., verbal versus nonverbal/spatial). From this, it was concluded that older adults' problems with dual tasking result from problems at the central stages of processing, with the greatest interference found for competing activities that call on the same processing resource. Details of the subgroups and effect sizes were not given in this study.

The current meta-analysis further examines age differences in dual task performance by trying to replicate the earlier studies by Kieley (1991, in Hartley, 1992) and Chen (2000). We expanded on the previous meta-analyses by reporting in more detail the task characteristics that might influence the magnitude of the age difference in dual task performance. To this end, we compare dual task studies that were either simple or relied on relatively automatic processing (e.g., perceptual tasks), with tasks that relied on controlled processing (e.g., episodic memory) or with tasks that had a motor component (e.g., tracking). Further details of the criteria for partitioning studies by task domain are described in the results section below. Our expectations were that a large overall effect size would be obtained but the effect sizes would not be homogeneous. It was also expected that tasks that required effortful controlled processing (relatively impaired in ageing) or had a significant motor component (previously identified as a potential moderator) would have a larger effect size than those studies using relatively automatic or data driven tasks (relatively intact in ageing). In line with the two previous meta-analyses a comparison between the reaction time data and the accuracy data was carried out. Also, since baseline differences in primary and secondary task performance could be a potential confound we consider this as a moderator variable.

METHOD

Literature search

A computer-based search was carried out using the Web of Science bibliographic database. Using both the science and social science citation index, and using the screening procedure described below, 62 effect sizes were extracted from 34 papers. This was achieved by performing a keyword search using various combinations of terms such as ''dual task'', ''dual tasking'', ''divided attention'', ''ageing'', ''older adults'', ''elderly'', etc. Fourteen studies reported by Kieley (1991, in Hartley, 1992) were not included in the present meta-analysis as they did not meet the inclusion criteria. Unfortunately, we were not able to establish whether all those studies examined by Chen (2000) were present in the current meta-analysis as critical details were missing. The published studies included in the meta-analysis are shown in Table 1.

TABLE 1

Component tasks, sample size, mean age of the younger and older participants, dependent variables, controls for baseline differences in performance, effect sizes, and method of calculation for 34 published articles between 1981–2003

Id	*Reference*	*Task one*	*Task two*	*Task*[1]	*N*	*Mean age*	*Dependent variable*	*Control for baseline differences*	d	d *calculation*
1 2	Wright (1981)	Digit load (vocal response)	Reasoning (manual response)	C C	12 12	19.4 68.2	Task one—accuracy Task two—accuracy (Experiment 1)	No No	2.15 0.93	Transformed age 6 condition (dual vs. single) *F*.
3	Salthouse and Somberg (1982)	Visual discrimination (manual response)	Auditory reaction time task (vocal response)	A	8 8	22.9 68.8	Task two—reaction time	No	4.08	Transformed age × condition *F*.
4	Somberg and Salthouse (1982)	Visual target detection (manual response)	Visual target detection (manual response)	A	16 16	19.8 65.1	POC[2] analysis—accuracy	Yes	0.25	Transformed age effect for mean divided attention costs *t*.
5	Macht and Buschke (1983)	Word recall after sorting	Visual reaction time (manual response)	C	48 48	19.6 70.3	Task two—reaction time	No	1.35	Transformed age effect on single vs. dual difference scores *F*.
6 7 8	Salthouse, Rogan, and Prill (1984)	Visual digit span (vocal response)	Visual letter span (vocal response)	C C C	24 24 16 16 16 16	18.9 69.5 18.6 70.1 19.1 66.6	POC analysis—accuracy	Relative	0.79 0.60 1.05	Transformed age effects for mean divided attention costs *t*.

9	Baddeley, Logie, Bressi, Della Sala, and Spinnler (1986)	Tracking	Auditory digit span (vocal response)	M	20 28	24.3 64.0	Task two—accuracy	Matching	0.32	Transformed age × condition interaction *F*.
10	McDowd (1986)	Tracking	Auditory reaction time (manual response)	M	6 6	22.5 69.5	Tasks one and two—time on target and reaction time	Relative	1.38	Transformed age effect for mean divided attention costs *F*.
11	Craik and McDowd (1987)	Cued recall and recognition (vocal response)	Visual reaction time task (manual response)	C	15 15	20.7 72.8	Task two—reaction time (across recognition and recall)	Relative	0.65	Transformed age effect for mean divided attention costs *F*, in age by test type interaction.
12	Guttentag and Madden (1987)	Letter matching (manual response)	Tone detection (manual response)	C	14 14	19.9 68.9	Task two—reaction time	Relative	0.99	Transformed age effect for mean divided attention costs *F*. Collapsed across difficulty.
13 14 15	McDowd and Craik (1988)	Auditory word monitoring (manual response) Auditory digit monitoring (vocal response)	Visual reaction time (manual response) Visual reaction time (manual response) Task A—as Experiment 1 Task B—faces tasks	C C C	16 16 18 18	19.4 69.0 21.0 71.9	Exp 1. Tasks one and two—reaction time Exp. 2. Task two—reaction time	Relative	1.31 2.00 0.72	Transformed age effect for mean divided attention costs *F*. collapsed across difficulty.

(Continued overleaf)

TABLE 1
(Continued)

Id	*Reference*	*Task one*	*Task two*	*Task*[1]	*N*	*Mean age*	*Dependent variable*	*Control for baseline differences*	d	d *calculation*
16	Lorsbach and Simpson (1988)	Letter matching task (manual response)	Auditory reaction time (manual response)	C	18 18	20.2 66.8	Task two—reaction time	No	2.14	Transformed age effect on single vs. dual difference scores *F*.
17	Ponds, Brouwer, and Vanwolffelaar (1988)	Tracking	Dot counting (manual response)	M	17 41	27.5 68.6	POC analysis—accuracy	Relative	0.74	Transformed age effect for mean divided attention costs *t*.
18	Baron and Mattila (1989)	Memory scan—visual and auditory (manual response)	Memory scan—visual and auditory (manual response)	C	12 12	18–25 65–76	Tasks one and two—reaction time	Relative	0.83	Transformed age effect for mean divided attention costs *F*.
19 20	Park, Smith, Dudley, and Lafronza (1989)	Word recall	Auditory digit monitoring—manual response	C C	64 62 16 16	19.0 72.3 18.8 67.3	Task one—accuracy	No	0.35 0.47	Transformed age × condition (single vs. dual at encoding) *F*.
21	Brouwer et al. (1990)	Tracking (steering)	Dot counting (manual response)	M	22 22	30.2 66.2	Tasks one two—accuracy—relative	Relative	0.84	Transformed age effect for mean divided attention costs *F*.

22	Mellinger, Lehman, Happ, and Grout (1990)	Recall visual and auditory words	Visual reaction time (manual response)	C	32 32	20 68	Task two—reaction time—proportionate	Relative	1.11	Transformed age effect for mean divided attention costs *F*.
23	Morris, Craik, and Gick (1990)	Word recall	Sentence verification (manual response)	C	16 16	21.4 71	Exp. 2. Task one—accuracy	No	0.68	Transformed age × condition interaction *F* collapsed across difficulty.
24 25	Brouwer, Waterink, Vanwolffelaar, and Rothengatter (1991)	Tracking	Visual reaction time task (manual and vocal responses)	M M	12 12	26.11 1 64.4	Task one—time on target Task two—accuracy relative	Relative	1.16 1.94	Transformed age effect for mean divided attention costs *F*.
26	Tun, Wingfield, and Stine (1991)	Speech recall	Manual reaction time	A A	18 18	18.3 69.6	Task one—accuracy	No	0.08 0.18	Calculated from recall scores collapsed across single and dual task difficulty.
							Task two—reaction time	No		Calculated from secondary task latencies collapsed across single and dual task difficulty.

(Continued overleaf)

TABLE 1
(Continued)

Id	*Reference*	*Task one*	*Task two*	*Task*[1]	*N*	*Mean age*	*Dependent variable*	*Control for baseline differences*	d	d *calculation*
27	Marquie and Baracat (1992)	Typing task	Auditory reaction time (manual response)	C	12 12	22.2 62.2	Task two—reaction time (proportionate)	Relative	1.02	Transformed age effect for mean divided attention costs *F*.
28	Hawkins, Kramer, and Capaldi (1992)	Visual reaction time (manual response)	Auditory reaction time (manual response)	A	14 14	27.5 68.0	Exp. 1. Tasks one and two—reaction time (time-sharing task)	Relative	1.17	Transformed age effect for mean divided attention costs *F*.
29 30	Tun, Wingfield, Stine, and Mecsas (1992)	Recall of spoken passages	Picture recognition	A A	25 25	20.3 68.0	Task one—accuracy Task two—reaction time	No	0.30 0.84	Transformed age × condition *F*.
31	Korteling (1993)	Tracking	Tracking	M	14 14	25.8 69.7	Tasks one and two—accuracy	Matching	1.10	Transformed age effect *F*.
32	Tun and Wingfield (1994)	Speech recall	Manual reaction time task	A	18 18	20.1 69.8	Task one—reaction time (items per second)	No	0.09	Calculated from retrieval times collapsed across single and dual task difficulty.
33 34 35	Kramer, Larish, and Strayer (1995)	Monitoring task (manual response)	Alphabet—arithmetic task (manual response)	C C C	29 30	20.8 67.8	Task one—reaction time Task one—accuracy Task two—reaction time	No	0.55 0.63 0.99	Pretraining age × task interaction *F*.

36 37 38	Light and Prull (1995)	Naming task	Number addition task (manual response)	A C A	24 24 48 48	21.2 72.0 21.8 73.6	Exp. 1. Task one—word naming—reaction time Free recall—accuracy Exp. 2. Task one—word naming—reaction time	No	0.11 0.43 0.08	Age × condition interaction *F*.
39 40 41	Salthouse, Fristoe, Lineweaver, and Coon (1995)	Letter memory	Visual reaction time (manual response)	C C C	40 40	20.9 66.8	Task one—accuracy Task two—accuracy Task two—reaction time	Relative	0.32 0.32 0.41	R^2 associated with age and mean divided attention costs, collapsed across difficulty.
42 43 44 45 46	Anderson, Craik, and Naveh-Benjamin (1998)	Free recall Cued recall Recognition	Visual reaction time task (manual response)	C C C C C	24 24 24 24 24 24	22.5 68.6 21.0 67.9 19.7 68.0	Exp. 1. Task two—reaction time Exp. 2. Task one—accuracy Task two—reaction time Exp. 4. Task one—accuracy Task two—reaction time	Relative	1.67 0.35 1.95 0.54 0.91	Main effect of age on divided attention costs (collapsed across encoding and retrieval conditions).
47	Batsakes and Fisk (2000)	Category search task	Pattern search task	C	24 24	21.0 71.6	Tasks one and two—accuracy	Matching	1.15	Age × condition interaction *F*. End of single vs. beginning of dual task training.

(Continued overleaf)

TABLE 1
(Continued)

Id	*Reference*	*Task one*	*Task two*	*Task*[1]	*N*	*Mean age*	*Dependent variable*	*Control for baseline differences*	d	d *calculation*
48 49	Clarys, Isingrini, and Haerty (2000)	Word completion Cued recall	Memory load Memory load	A C	24 24 24 24	30.8 74.7 30.8 74.7	Task one—accuracy Task one—accuracy	No No	0.06 0.42	Age × condition interaction *F*, collapsed across both implicit tasks.
50 51 52	Light, Prull, and Kennison (2000)	Category exemplar generation Category verification Recognition	Addition task at encoding Addition task at encoding	A A C	24 24 36 36	20.29 72.5 22.81 71.67	Task one—accuracy Task one—reaction time Task one—reaction time	No No No	0.14 0.10 0.69	Transformed age × condition *F*.
53 54	Lindenberger, Marsiske, and Baltes (2000)	Sensorimotor task	Serial recall—encoding	M M	47 48	24.0 65.0	Task one—walking speed Task two—accuracy	Relative	0.70 0.80	Transformed age effect *F* for relative DAC.
55	Li, Lindenberger, Freund, and Baltes (2001)	Sensorimotor task	Serial recall	M	37 40	25.1 65.6	Task two—accuracy	Relative	1.09	Transformed age effect *F* for relative DAC.

56	De Ribaupierre and Ludwig	Perceptual	Target	A	81	23.17	Task two—accuracy	Relative	0.91	Transformed R^2
57	(2003)	clarification—	detection—	A	86	72.24	Task one—reaction		0.46	associated with
58		vocal response	manual	A			time		0.55	age and relative
59		Sentence	response	M			Task two—accuracy		0.11	divided attention
60		verification	Word span	M			Task one—accuracy		0.46	costs.
61		Verbal span	Tracking	M			Task two—accuracy		0.81	
62		Sensorimotor	Sensorimotor	M			Task one—accuracy		0.46	
		task	task				Task two—accuracy			

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[1] C, A, and M represent controlled, automatic, and motor processing tasks, respectively.

[2] POC—performance operating characteristic.

Inclusion criteria

Published articles between 1981 and 2003.

Studies comparing one group of healthy younger adults (approximate range 18–35) and one group of healthy older adults (approximate range 60–85).

Studies containing tests and measurement of both single and dual task performance on either or both the primary and secondary task. A baseline single task score is essential for a precise assessment of dual tasking ability (see Salthouse et al., 1995).

Studies with adequate data to compute effect sizes from either descriptive or inferential statistics.

Effect size calculations

The majority of the studies did not report means and standard deviations necessary for the calculation of the effect size. Therefore, effect size estimates were calculated from statistics such as F, t, and r (see Wolf, 1986, for formula). This approach has been used in previous meta-analyses for converting test statistics to an estimate of effect size d (e.g., Light, Prull, La Voie, & Healy, 2000). The effect size d[2] in the current study refers to the standardised difference between the younger and older adults mean dual task performance on either the primary or secondary task (i.e., absolute or relative differences between single and dual task score). The effect size estimation d and method of calculation is reported for each study in Table 1. In some cases more than one effect size was extracted from a study. Although caution has been advised regarding the analysis of nonindependent effects (e.g., Wolf, 1986), we included all effects from a particular study if the data were available. Besides, it has been argued that the nonindependence violation does not greatly affect statistical precision (Block, Zakay, & Hancock, 1998; Tracz, Elmore, & Pohlmann, 1992).

A meta-analysis was carried out using the procedures described by Hedges and Olkin (1985). The first aim of the meta-analysis was to decide whether the studies shared the same overall effect size. This was achieved by calculating the fit statistic Q_T. If the fit statistic is significant this demonstrates that the effect sizes are not homogeneous across studies and a second stage of processing is required. In particular, a significant effect suggests that there are different factors contributing to the magnitude of the effect size. If Q_T is not significant the process stops and the average effect size is viewed as an accurate representation of all the studies reported.

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[2] The unadjusted effect size was used in the present analyses. However, separate analyses using the correction outline by Hedges and Olkin (1985) did not alter any of our conclusions so they are not reported here.

In the second stage of the analysis, the studies are partitioned into subgroups based on what are believed to be the most important factors contributing to the magnitude of the effect size. For instance, in the current investigation we hypothesise that task type moderates the age effect. An analysis is then performed to compare the effect sizes within and between the subgroups much like a standard analysis of variance. That is, the within (Q_W) and the between (Q_B) group fit must be calculated and evaluated. The fit statistic Q_W is calculated so that we can ascertain whether the studies within the subgroups have to be partitioned further. A significant Q_W statistic suggests further factors contribute to the variability in the effect sizes. A nonsignificant effect indicates that the moderator sufficiently accounts for the variability. Once homogenous groups are found, the between group statistic Q_B is calculated and represents the difference in the magnitude of the effect size between subgroups.

RESULTS

Overall effect size

The first aim of the meta-analysis was to calculate the overall mean effect size (*d*) and then determine whether this measure fully captures our data set. Figure 1 shows the distribution of 62 effect sizes (*d)* from 34 studies, involving a total of 1073 younger adults and 1113 older adults. The mean weighted effect size[3] was $d = .68$, with a 95% confidence interval from .62 to .75. To determine whether this mean weighted effect size was a good representation of the effect sizes from each study, the fit statistic Q_T was calculated. This analysis demonstrated that the effect sizes were heterogeneous, $Q_T(61) = 245.5$, $p < .01$. In order to determine whether the presence of outliers was responsible for the heterogeneity a further analysis was carried out with one effect size removed (No. 3 in Table 1). The effect size was judged as an outlier based on visual inspection of the data. No other effect size estimate had a 95% confidence interval overlapping the outlier. With one outlier removed, the mean weighted effect size was .69, with a 95% confidence interval from .60 to .73. To determine whether this mean weighted effect size was a good representation of the effect sizes from each study, the fit statistic Q_T was calculated. This analysis demonstrated that the effect sizes were heterogeneous and therefore the presence of the outlier was not responsible for the variability, $Q_T(60) = 199.12$, $p < .01$. Although the outlier was not responsible for the heterogeneity it was clearly deviant (see Figure 1). Therefore, subsequent analyses reported below are based on the data with one outlier removed (No. 3 in Table 1).

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[3] When calculating the mean effect size, those studies with larger *n* receive more weight (see Hedges & Olkin, 1985, pp.109–117).

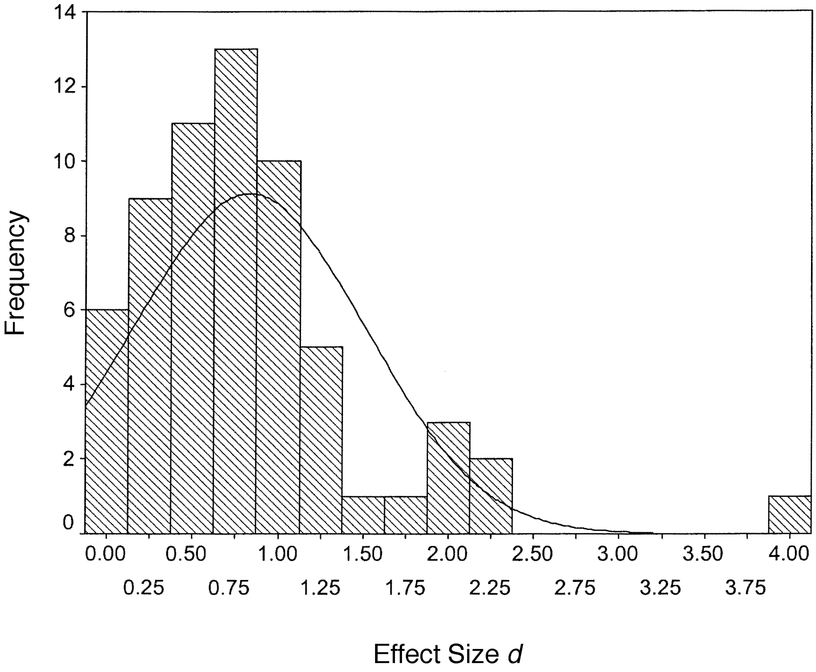

Figure 1. The distribution of the effect sizes (*d*).

Moderator variable search

After removing one outlier the weighted mean effect size was a poor fit to the data, therefore it was necessary to investigate the variability in more detail. We begin by reporting analyses based on subgroups divided according to the dependent variable (reaction time versus accuracy), and then by whether baseline differences in performance had been controlled for. However, the main aim of the present study is the examination of task domain as a potential moderator. Thus, our main analysis will focus on the magnitude of effect sizes across three task groups (''controlled processing'', ''simple perceptual or relatively automatic'', and ''substantial motor component''). All planned comparisons were conducted using the Bonferroni procedure at a significance level of $p < .05$.

Dependent variable of response latency and accuracy

Partitioning the effect sizes by dependent variable produced one group of 34 effect sizes based on accuracy and one group of 26 effect sizes based on response latencies. The mean weighted effect size for the accuracy group was

.59, with a 95% confidence interval from .51 to .67. The mean weighted effect size for the response latency group was .78, with a 95% confidence interval from .68 to .89. One effect size (No. 10 in Table 1) was removed from the analysis as the effect size represented a combined measure of the accuracy and response latency for the two component tasks in the study. Since the overall fit statistic Q_T was statistically significant in the overall analysis, $Q_T(59) = 197.59$, $p < .01$, the within-group statistics Q_W and the between-group statistic Q_B were calculated. The first analysis investigated the homogeneity of effect sizes within groups and demonstrated that there was a lack of fit, $Q_W(58) = 189.17$, $p < .01$. Each group was then examined for poor fit. This analysis demonstrated that the effect sizes within the accuracy group, $Q_w(33) = 75.06$, $p < .01$, and the latency group, $Q_w(25) = 114.12$, $p < .01$, were heterogeneous. At this point it would be necessary to partition the accuracy and reaction time groups further to investigate other potential moderator variables. This will be examined under the task domain section below. The next analysis investigated the between group fit Q_B and showed that there was a difference in the effect sizes between groups, $Q_B\ (1) = 8.4$, $p < .01$. This analysis gives some indication that the nature of the dependent variable used, accuracy or response latency impacts upon the overall magnitude of the age effect observed in dual task costs, albeit on heterogeneous groups.

Controls for baseline differences in performance

One possible source of variation in the effect size estimates is whether investigators have controlled for baseline differences in performance. Without such control it is difficult to establish whether any age-related difference in performance is due to a general performance decrement or a specific problem in dual tasking. However, the method by which control has been achieved varies across studies. Some studies have controlled for baseline performance by using proportional measures of divided attention costs, whilst others have striven to match performance at baseline by various means.

Partitioning the effect sizes, by whether baseline difference in performance had been controlled for, produced one group of 22 effect sizes based on absolute measures of performance, one group of 35 effect sizes based on relative (proportionate) measures of performance and four studies using matching procedures. The mean weighted effect size for the group where absolute differences in performance were analysed was .55, with a 95% confidence interval from .44 to .67. The mean weighted effect size for the group where relative measures of performance were used was .73, with a 95% confidence interval from .65 to .81. Finally, the mean weighted effect size for the group where matching procedures were used was .61, with a 95% confidence interval from .38 to .85. Since the overall fit statistic Q_T was statistically significant in the overall analysis the within-group statistics Q_W and the between-group statistic Q_B were calculated.

The within-group analysis demonstrated that there was a lack of fit within groups, $Q_W(58) = 192.61$, $p < .01$. Each group was then examined for poor fit. This analysis demonstrated that the effect sizes for the absolute, $Q_w(21) = 81.92$, $p < .01$, and relative, $Q_w(34) = 103.6$, $p < .01$, groups were heterogeneous. The effects were homogeneous for the matching group, $Q_w(3) = 7.1$, $p > .05$. The between-group analysis showed that there was a difference between the effect sizes between groups, $Q_B(2) = 6.51$, $p < .05$. Planned comparisons using the Bonferroni procedure found significant differences between the absolute and relative group. There was no difference between the relative and matching procedures groups, or between the matching and absolute groups.

Thus, contrary to what one might expect from the work of Somberg and Salthouse (1982), there is an overall larger effect size in those studies that controlled statistically for baseline differences in performance, between age groups. Importantly, it must be recognised that the nature of the tasks studied also interacts with the presence/absence of control for baseline differences. Table 2 show the effect sizes and *n* for each method of baseline control, across task type. These data give some indication of how task type might influence the magnitude of the effect size across method of baseline control.

Task domain

The aforementioned analyses demonstrated that dependant variable used and method of baseline control influence the size of the age effect. However, in some cases significant within-group fit statistics remained and therefore the results should be treated with caution. Importantly, a further moderator search is desirable to account for the remaining variability. Therefore, a further analysis was carried out to investigate whether component task type in the dual task

TABLE 2
The effect size and *n* for each method of baseline control, across task type

Task type	*Method of baseline control*	*Effect size (d)*	*Number of effect sizes (n)*
Control	Proportionate dual task cost	0.92	19
	Absolute dual task costs	0.91	13
	Matching procedures	0.76	1
Automatic	Proportionate dual task cost	0.67	5
	Absolute dual task costs	0.19	9
	Matching procedures	—	0
Motor	Proportionate dual task cost	0.91	11
	Absolute dual task costs	—	0
	Matching procedures	0.63	3

situation is critical. An examination of Table 1 shows that few studies use identical tasks and combinations. Therefore, three broad classes of task groups were constructed based largely on the primary task used. Table 1 shows the group to which each study was assigned, and the criteria for partitioning the effect sizes are described below.

Clearly, there are numerous ways in which we could partition the groups based on task characteristics. A desirable analysis would be to partition studies into groups if they used the exact same task combination and procedures. Unfortunately, few studies have used the same procedures rendering this analysis impractical because partitioning groups in this way would yield low numbers in each task group. Here, we use the broad criteria below but report details of the task combinations in Table 1, allowing researchers to test their own hypotheses.

Criteria

Controlled processing group. One or both of the component tasks draw substantially on ‘‘controlled/executive’’ processing mechanisms. Lindenberger et al. (2000) suggest when one or both of the component tasks in themselves draw on executive controlled type processes we might expect heightened dual task costs for older adults, since task coordination is a putative executive ability. In addition, Kieley (1991, in Hartley, 1992) and Chen's (2000) investigations pointed to dual tasks involving central or controlled processing being problematic for older adults. Effect sizes allocated to this group included those tasks with a high working memory load, episodic memory tasks and reasoning tasks.

Automatic processing group. One or both of the tasks are relatively automatic or data driven. For example, choice reaction time and implicit memory tasks. In addition, those tasks involving information processing mechanisms reported to be relatively well preserved in ageing, or on those tasks where older adults can capitalise on overlearned processes, or environmental support. For example, those tasks involving language processing (see review by Tun & Wingfield, 1993) and those tasks with a large semantic memory component.

Motor processing group. One or both of the tasks have a large motor component. Given that studies have reported dual task difficulties in everyday activities involving motor performance, such as memorising while walking (Lindenberger et al., 2000) and driving (e.g., Brouwer, Ickenroth, Ponds, & Vanwolffelaar, 1990) it was important to consider the sensorimotor domain. In addition, the earlier meta-analysis carried out by Kieley (1991, in Hartley, 1992) also pointed to those tasks involving motor processing causing greater dual task impairment. Tasks involving walking and simple motor movements like tracking were included in this group.

Partitioning the effect sizes by task group produced one group of 33 effect sizes based on tasks with a large controlled processing component, 14 effect sizes based on tasks which relied on relatively automatic processing, and 14 effect sizes based on tasks that had a large motor component. The mean weighted effect size for controlled processing was .84, with a 95% confidence interval from .75 to .94. The mean weighted effect size for automatic processing was .42, with a 95% confidence interval from .3 to .55. The mean weighted effect size for motor processing was .64, with a 95% confidence interval from .52 to .75. Figure 2 shows the distribution of these effect sizes for each of the three task groups. Since the overall fit statistic Q_T was statistically significant, in the overall analysis the within-group statistic Q_W and the between-group statistic Q_B were calculated. The within-group fit statistic demonstrated that the effects sizes were heterogeneous within classes, $Q_W(58) = 171.14$, $p < .01$. The effect sizes were heterogeneous in the controlled processing, $Q_W(32) = 106.8$, $p < .01$, automatic, $Q_W(13) = 27.49$, $p < .01$, and motor, $Q_W(13) = 36.85$, $p < .01$, groups. The next analysis investigated the homogeneity of effect sizes across groups. In this analysis Q_B was higher than the 95% critical value of the chi-squared distribution and showed that there was a significant difference between effect

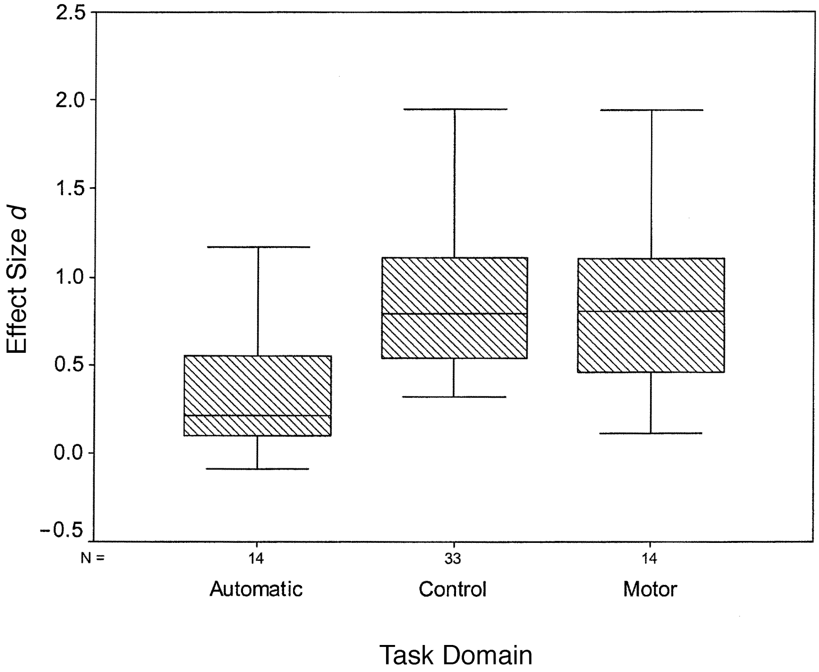

Figure 2. The distribution of effect sizes (*d*) for the three task groups.

sizes between groups, $Q_B(2) = 27.98$, $p < .01$. Secondary analyses, using the Bonferroni method, demonstrated significant differences between the automatic group and the controlled processing group. The differences between the motor and automatic group approached significance. There was no difference between the motor and controlled processing groups.

Since, dependent measure used was previously found to be a significant moderator variable it could be argued that combining reaction time and accuracy measures is inappropriate, and may account for the remaining variability within groups described above. The analysis was therefore repeated across reaction time and accuracy groupings. However, a note of caution must be that this necessarily reduces the number of studies that enter into each cell of the comparisons.

Reaction time data

Partitioning the effect sizes by task group produced one group of 17 effect sizes based on tasks with a large controlled processing component, 8 effect sizes based on tasks which relied on relatively automatic processing, and 1 effect size based on tasks that had a large motor component. The mean weighted effect size for controlled processing was 1.1, with a 95% confidence interval from .96 to 1.23. The mean weighted effect size for automatic processing was .31, with a 95% confidence interval from .13 to .48. The effect size for motor processing was .70. Note the motor processing group contained only one study and therefore is not considered in the analysis below. Since the overall fit statistic Q_T was statistically significant in the overall analysis, $Q_T(24) = 113.93$, $p < .01$, the within-group statistic Q_w and the between-group statistic Q_B were calculated. The within-group analysis demonstrated that there was a lack of fit within groups, $Q_W(23) = 64.6$, $p < .01$. Each group was then examined for poor fit. The fit statistic Q_W demonstrated that the effects sizes were heterogeneous in the controlled processing group, $Q_W(16) = 52.45$, $p < .01$, and homogenous in the automatic group, $Q_W(7) = 12.22$, $p > .05$. Visual inspection of the data identified three outliers in the controlled processing group (Nos. 14, 16, and 44). The analysis was re-run with these outliers removed. The corrected effect sizes for the controlled processing group was .94, and the effects were now homogeneous, $Q_W(13) = 22.21$, $p > .05$. The next analysis investigated the homogeneity of effect sizes across the automatic and controlled processing groups. In this analysis Q_B was higher than 95% critical value of the chi-squared distribution and showed that there was a significant difference between effect sizes between groups, $Q_B(1) = 29.56$, $p < .01$. Figure 3 shows the distribution of these effect sizes for each of the three task groups.

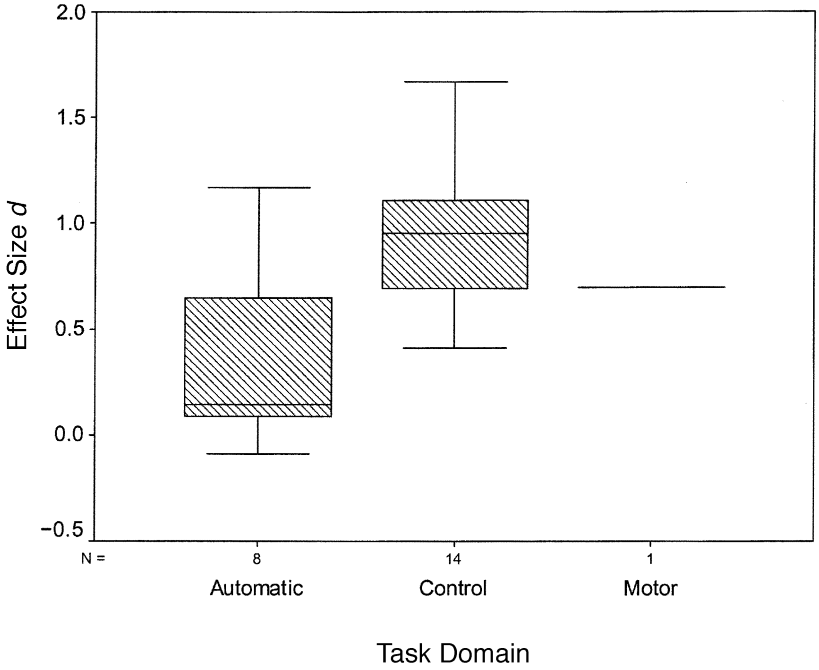

Figure 3. The distribution of effect sizes (*d*) for the three task groups for reaction times.

Accuracy data

Partitioning the effect sizes by task group produced one group of 16 effect sizes based on tasks with a large controlled processing component, 6 effect sizes based on tasks which relied on relatively automatic processing, and 12 effect sizes based on tasks that had a large motor component. The mean weighted effect size for controlled processing was .58, with a 95% confidence interval from .45 to .72. The mean weighted effect size for the automatic processing group was .54, with a 95% confidence interval from .37 to .71. The effect size for the motor processing group was .63 with a 95% confidence interval from .50 to .75. Since the overall fit statistic Q_T was statistically significant in the overall analysis, $Q_T(33) = 75.06, p < .01$, the within-group statistic Q_W and the between-group statistic Q_B were calculated. The within-group analysis demonstrated that the effects sizes were heterogeneous, $Q_W(31) = 74.40, p < .01$. Each group was then examined for poor fit. This analysis demonstrated that the effect sizes for the controlled processing, $Q_w(15) = 27.53, p < .05$, automatic, $Q_w(5) = 11.79, p < .05$, and motor, $Q_w(11) = 35.07, p < .01$, groups were heterogeneous. Visual inspection of the data revealed one outlier in the controlled processing group, one outlier in the automatic group and two outliers in the motor group. Only one other effect size had a 95% confidence interval overlapping the outlier in the motor group and none in the automatic and controlled processing groups. An additional outlier (No. 58 in Table 1) was removed as it was clearly deviant when a plot of the distribution of the effects was inspected. The analyses were re-run with one outlier removed from the controlled processing (No. 1), two outliers (Nos. 56 and 58) removed from the automatic group, and two outliers (Nos. 25 and 59) removed from the motor group. The corrected estimate for the control group was .54 with a 95% confidence interval between .40 and .68. The corrected estimate for the automatic group was .18 with a 95% confidence interval from –.11 to .48. The corrected estimate for the motor group was .69 with a 95% confidence interval from .55 to .82. With outliers removed, there was homogeneity within groups, $Q_w(26) = 25.53$, $p > .05$. Figure 4 shows the distribution of these effect sizes for each of the three task groups. In the final analysis, Q_B was higher than 95% critical value of the chi-squared distribution and showed that there was a significant difference between effect sizes between groups, $Q_B(2) = 9.92$, $p < .01$. Secondary analyses, using the Bonferroni method demonstrated significant differences between the automatic group and the controlled processing groups, and between the motor and automatic groups. There was no difference between the motor and controlled processing groups.

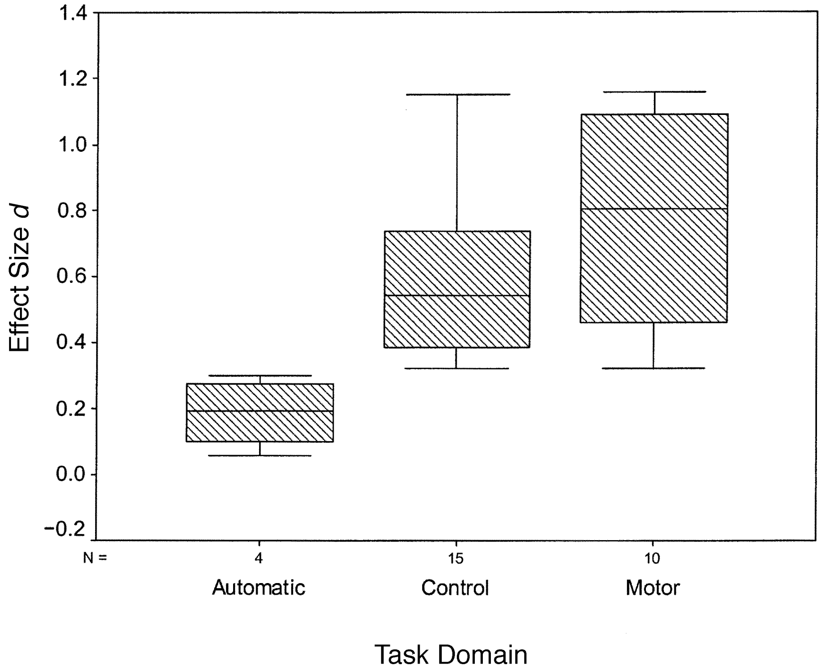

Figure 4. The distribution of effect sizes (*d*) for the three task groups for accuracy.

DISCUSSION

The aims of this meta-analysis were to examine the magnitude of the age differences in dual task performance and to examine whether the combined effect size estimate was a good representation of the pattern of results across studies. However, the effect sizes were found to be heterogeneous, and so it was necessary to analyse the role of moderator variables that may have influenced the variability in effect sizes across studies. We chose to use the procedures outlined by Hedges and Olkin (1985) to partition effect sizes into rationally derived subgroups and examine the fit within and between groups.

Consider first the mean weighted effect size calculated from the 34 published articles. The effect size was particularly high at .68, which simply represents the standardised mean difference between younger and older adults' dual task performance. As noted earlier, effect sizes of .2, .5, and .8 are considered low, medium, and high, respectively (Hedges & Olkin, 1985). This result is similar to the findings by Kieley (1991, in Hartley, 1992) and Chen (2000), who found mean effect sizes of .99 (*d*) and .79 (*g*) respectively, thus the replication was achieved. Like these two earlier meta-analyses, we sought to explain the variability in the effect sizes across studies by considering task characteristics. Importantly, our investigations extended previous research significantly by examining task domain and method of control for baseline performance.

The problem for procedures that attempt to investigate age differences in dual tasking are that methodological variations are frequent and numerous task combinations have been employed. Therefore, these factors were considered in the present meta-analysis. Effect sizes were first partitioned into groups according to the dependent measure used. Consistent with Chen (2000), we found that the effect size was greater when a reaction time measure was used (.78 and .59 for reaction time and accuracy, respectively). This finding is what would be predicted if older adults were more concerned with maintaining accuracy rather than speed on cognitive tasks (e.g., Smith & Brewer, 1995). Therefore, in the context of a dual task we might expect to find a larger overall effect size when performance is assessed by a response time measure. Regardless, the magnitude of the effect size was substantial for both response time and accuracy.

Somberg and Salthouse (1982) were one of the first to criticise the majority of findings regarding age differences in dual task performance, as generally early studies failed to take into account baseline differences in performance on the component tasks. When the studies were partitioned into groups according to method of baseline control the mean effect size for the absolute group was the smallest. This was somewhat surprising; one would have expected the effect size based on absolute differences in performance to be greater than that when a proportional or relative measure was used. This would be consistent with studies that have initially observed age differences in dual task performance, but found that this difference was eliminated when using a proportional or relative measure (e.g., Somberg & Salthouse, 1982). Chen (2000) did compare the few studies that reported both measures and found similar effect sizes. Their analysis found the opposite pattern expected when studies reported either absolute or relative measures of performance. This pattern can be accounted for by examining Tables 1 and 2, which clearly shows that task type interacts with method of statistical control for baseline differences in performance. That is, the automatic processing groups (e.g., language processing and implicit memory tasks) largely used absolute measures of performance. However, the control group used mainly a proportionate dual task costs measure. The aforementioned comparison is therefore problematic due to the groups being highly related to task type. Notably, when the method of baseline control (relative versus matching) was compared the effect sizes were equivalent, thus giving no insight into the relative merits of each method of control (for a discussion of metric selection, see Guttentag, 1989).

Our main concern was the examination of task as a moderator variable of dual task costs in older adults. Categorising the studies into groups was problematic, as there has been a large variety of tasks and combinations used, and there are no accepted clear definitions of what constitutes a particular task type. Therefore, two broad classes were constructed to include tasks requiring primarily ‘‘controlled’’ processing or ‘‘automatic’’ processing. By comparing these two groups we could assess whether cognitive domains that are impaired versus spared in ageing influence dual task performance. In addition, a third group comprising tasks that required largely motor processing was created. Our reasoning here was that previous research (particularly driving studies) has found that older adults find coordinating motor tasks problematic. The results were in line with our expectations. Those tasks with a substantial controlled processing element produced a large effect size of 1.1 and .58 for response time and accuracy, respectively. Those tasks with a large memory component in particular formed the majority of the controlled processing group. The mean effect size from the automatic processing group produced effect sizes of .31 and .54 for response time and accuracy, respectively. Again our results were in line with previous research, which has found either no or small age differences in dual task performance in domains of cognition that rely on overlearned or relatively automatic processing. This is consistent with Tun and Wingfield (1993), who found that when meaningful language was involved, task difficulty manipulations (such as divided attention) had little effect on the performance of younger or older adults. Importantly, the abovementioned consideration is consistent with a large body of cognitive ageing research pointing to the distinction between automatic and controlled modes of processing (e.g., Jennings & Jacoby, 1993).

Our final task group consisted of those tasks where motor processing is primarily required and much like the controlled processing group a large overall effect size was produced (d = .98). This finding is consistent with previous research that has found age effects both at the cognitive and motor processing level (e.g., Crook, West, & Larrabee, 1993). Furthermore, it has been identified that when complex tasks (e.g., driving) require motor skills, older adults are particularly impaired (e.g., Korteling, 1991). Indeed, Lindenberger et al. (2000) in their investigations suggest that a decline in sensorimotor processing in ageing results in more controlled type processing mechanisms being called for and therefore when faced with competing demands older adults are particularly impaired due to a deficit in executive control.

Although there is broad consensus that under certain conditions dual tasking is problematic for older adults, the mechanisms responsible for the impairment is a little less clear. The key idea presented here is that task domain is critical in moderating age differences in dual task performance. Significantly, since old age brings about a decline in executive abilities (planning, monitoring, and coordinating ongoing activities), those tasks that show greatest impairment with ageing are more difficult to perform in the face of competing activities. However, in domains of cognition that are well preserved in ageing, older adults are able to capitalise on intact function and lessen the burden of executive control processes responsible for dual task coordination. The discussion of domain specific effects is also consistent with previous research on single tasks which has outlined, for example, the distinction between lexical and nonlexical tasks (e.g., Lima et al., 1991), implicit and explicit memory (e.g., Light, 1991), and automatic versus controlled modes of processing (e.g., Jennings & Jacoby, 1993), with greater dual task interference expected in the latter in each case.

The findings of the present meta-analysis have highlighted the usefulness of such techniques in integrating data from a number of studies. Such procedures enable the comprehensive review of studies relating to a particular hypothesis; here, are there age differences in dual task performance? As well as being able to investigate the magnitude and reliability of a combined effect size, such an analysis enables the examination of the influence of moderator variables within each task. In the present study this is invaluable as in the dual task ageing literature there have been mixed findings. What should be noted, however, is that the meta-analysis techniques used in the present investigation involves a series of main effect analyses. There is the possibility of interactions with the other factors (or possible confounds). For instance, it was found that certain task domains are associated with certain methods of baseline controls. Despite this, the techniques used in the present meta-analysis enable a summary of the literature against which future studies can be judged.

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