Multiple processing limitations underlie multitasking costs

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Background. Human multitasking is typically defined as the practice of performing more than one task at the same time (dual-task) or rapidly alternating between multiple tasks (task switching). The majority of research in multitasking has been focusing on individual paradigms, with surprisingly little effort in understanding their relationships.

Methods. We adopted an individual-differences approach to reveal the limitations underlying multitasking costs measured in different paradigms.

Results. Exploratory factor analyses revealed not a general multitasking factor but instead three different processing limitations associated with response selection, retrieval and maintenance of task information, and task-set reconfiguration. The three factors were only weakly correlated with and thus not reducible to common measures of processing speed, working memory capacity and fluid intelligence. Males and females excelled in different aspects of multitasking, demonstrating the benefit of using a multifaceted view of multitasking competency in group comparison.

Discussion. Findings of the current study help resolve conflicting results between studies using different paradigms, and form the basis of more comprehensive measurement tools and training protocols covering different aspects of multitasking limitations. The study will also help future integration of multitasking abilities into the theoretical framework of executive function.

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Abstract

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Keywords: multitasking, dual-task performance, task switching, factor analysis, individual differences

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1. Introduction

Driving while talking on a cell phone, resuming work after email checking, juggling between web browsing and instant messaging, etc., exemplifies the increasingly common practice of multitasking with the advance of technology and changes in lifestyle (Foehr, Rideout, & Roberts, 2005), with frequent undesirable consequences. For example, driving while talking on the cell-phone quadruples the probability of being involved in a collision (Redelmeier & Tibshirani, 1997), and toggling several tasks impairs learning and productivity (Hembrooke & Gay, 2003; Sana, Weston, & Cepeda, 2013). The majority of research on multitasking performance has focused on performance detriment in specific multitasking situations. While different paradigms all point to some kind of central cognitive limitations, it is unknown how they relate to each other. Do multitasking costs measured in different paradigms reflect a general limitation, or limitations at different stages of information processing? The current study represents the first attempt to reveal the underlying constructs behind the costs measured in different multitasking paradigms.

1.1. Various Multitasking Paradigms

Human multitasking can be defined as the practice of performing more than one task at the same time (concurrent multitasking or dual-task), or rapidly alternating between multiple tasks (task switching). Similarly the majority of laboratory studies of multitasking fall into these two categories.

One of the concurrent multitasking paradigms, the psychological refractory period (PRP) paradigm, involves successive presentation of two stimuli (S1 and S2) presented with a stimulus onset asynchrony (SOA) typically ranging from 0 to 1000 ms (e.g. Pashler, 1994). Participants have to respond to the two stimuli (i.e., S1 and S2 while performing Tasks 1 and 2 respectively) as fast as possible while maintaining near perfect accuracy. While response times to S1 (RT1) are generally constant across different SOAs, response times to S2 (RT2) are typically longer as S2 appears closer in time to S1. The PRP effect, defined as the RT2 difference between the long- and short-SOA trials, has been attributed by most researchers to either a stubborn bottleneck in response selection (Pashler, 1994; Pashler & Johnston, 1989) or a strategic deferment of the second response (Meyer and Kieras, 1997). A similar, equal priority dual-task paradigm (Dux et al., 2009; Schumacher et al., 2001; Tombu and Jolicoeur, 2004) also involves two tasks but the stimuli are presented at the same time and participants are instructed to give equal priorities to responding to both tasks. The equal-priority dual-task cost is defined as the RT difference between trials in which responses to both vs. one of the stimuli are required, i.e., dual-task vs. single-task trials. Another indicator, referred as the heterogeneity cost in the current study (or task-set cost in some studies, e.g., Bherer et al., 2008), was computed as the RT difference between single-task trials in a block where both single-task and dual-task trials can appear (dual-task blocks) and single-task trials in a block where there can only be one task (single-task blocks). Some researchers of dual-task performance have adopted paradigms with more continuous tasks, such as simulated driving while performing secondary tasks including cell phone conversation (e.g. Shinar, Tractinsky & Compton, 2005; Strayer and Johnston, 2001), choice task (Levy, Pashler, & Boer, 2006), and working memory span task (Alm and Nilsson, 1995).

The task switching paradigm was first introduced by Jersild (1927) in which participants were asked to alternate between two simple tasks. Performance was generally worse when the participants alternated between two tasks (switch trials) than when they worked on one task repeatedly (repeated trials), and the response time difference was defined as the switch cost. While the switching in this study was predictable, the majority of later studies involved unpredictable, cued switching, in which the task to be performed for each trial was indicated by a task cue presented right before the stimuli appeared. The switch cost has been proposed to come from task-set reconfiguration (Rogers & Monsell, 1995), which involves retrieving the task goals as well as tuning the different processing modules for the current task. Later studies (Logan & Bundesen, 2003; Mayr & Kliegl, 2003) have introduced a variant of the task switching paradigm (with two cues mapping to each task) with unpredictable switching to dissociate the cost due to the switch of the cue and that due to the switch of the task (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). Apart from the switch costs, mixing costs are often calculated by subtracting the average RT of the single-task trials within a single-task block from that of the repeated trials within a mixed-task block. The mixing cost is supposed to reflect performance detriment due to the simultaneous maintenance of two task-sets rather than one (Mayr, 2003). Other studies also impose additional requirements on the tasks to better mimic real-life situations, for example, by requiring one to maintain intermediate solutions of the current task while switching to another task (Borst, Taatgen, and van Rijn, 2010).

1.2. Processing Limitation(s) Underlying Different Paradigms

Do multitasking costs measured in different paradigms reflect one general or multiple separable processing limitations? Integrated theories of multitasking seem to allow both possibilities (Logan & Gordon, 2001; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). For example, the threaded cognition theory (Salvucci & Taatgen, 2008) proposes three types of processing resources: perceptual, cognitive and motor. The cognitive resources consist of a declarative module (for long-term factual knowledge storage) and a central procedural resource module (for information integration and processes initiation) as well as their corresponding buffers for temporary information storage. On the one hand, given the multiple modules and buffers involved in the cognitive processes, it is natural to speculate multiple processing limitations underlying different aspects of multitasking performance. On the other hand, as one main responsibility of the central procedural resource module is to initiate new processing on other resources, the central procedural resource can be regarded as a general multitasking limitation.

Some researchers assume implicitly a general processing limitation underlying multitasking costs measured in different paradigms. For example, a popular claim is that habitual multitaskers possess a general, breadth-biased processing style leading to impaired performance in different cognitive control tasks (Lin, 2009; Lui & Wong, 2012; Ophir, Nass, & Wagner, 2009). Another example concerns gender comparison in multitasking. Colom, Martinez-Molina, Shih, and Santacreu (2010) claimed that males are better than females at multitasking in general, based on males' better performance on only one concurrent multitasking paradigm. Interestingly though, Stoet, O'Connor, Conner, and Laws (2013) used a task switching paradigm instead and reached an opposite conclusion. One could argue that the conflicting findings were caused by differences in the background and past experience of the participants. A probable alternative, however, is that the multitasking costs measured in the two paradigms reflect different underlying processing limitations of multitasking, and males and females are superior in distinct aspects of multitasking. A recent study (Redick et al., 2016), which examined the relationship between multitasking and several cognitive abilities, has identified a general multitasking ability among three relatively complex multitasking paradigms including the SynWin test (Elsmore, 1994), the control tower task (Redick et al., 2013), and the air traffic control-lab task (Fothergill, Loft, & Neal, 2009). Yet the authors also identified merely moderate correlations among the costs in the different tasks, suggesting separable aspects of multitasking probed by different paradigms.

Could the costs measured in concurrent multitasking and task switching paradigms reflect two separate processing limitations respectively? Pashler (2000) pointed out that the magnitude of the PRP effect is larger than that of the switch cost, despite the occurrence of task-set overlap in both paradigms. Therefore, the larger amount of dual-task interference in concurrent multitasking point to limitations in addition to those related to task-set reconfiguration as in task switching. One may however question the usefulness of directly comparing the magnitude of the PRP effect and the switch cost, given the very different paradigms involved. Band and van Nes (2006) examined the relationship between the PRP effect and task switching. In their hybrid PRP paradigm, Task 2 was the same as Task 1 for half of the trials and different for the other trials. As a result, the PRP effect could be compared between the two conditions with and without a task switch from Task 1 to Task 2. Since the PRP effect did not differ across the two conditions, it was concluded that task switching does not contribute to the dual-task interference measured in the PRP paradigm. In addition, Miyake et al. (2000) found that mental set shifting indicated by the switch cost of the task switching paradigm was not correlated with dual-task performance.

Yet another alternative is that multitasking costs come in more than two types and are not organized exactly in terms of concurrent multitasking vs. task switching. For example, there have been debates on the potentially separable processing stages in task switching. In task switching studies with a 2:1 mapping between cues and tasks, the compound-cue retrieval account (e.g. Logan & Bundesen, 2003; Logan & Schneider, 2010) denies the existence of executive control processes and suggests that cue-switch and task-switch processes represent a continuum of the compound-cue encoding and priming processes. However, multiple-component models (e.g., Jost, Mayr, & Rosler, 2008; Mayr & Kliegl, 2003; Schmitz & Voss, 2014) suggest that the task switching process can be further decomposed into two distinct cognitive stages involving a cue-driven memory retrieval stage of task-set and a stage in reconfiguring and applying the new task-set. Training studies also demonstrated a pattern of transfer effects more complicated than a simple concurrent multitasking vs. task switching dichotomy can explain. Strobach, Frensch, Soutschek, and Schubert (2011) showed that practice on an equal priority dual-task paradigm led to a transfer effect on the mixing cost but not the switch cost, although both were measured in the same task switching paradigm. Lussier, Gagnon, and Bherer (2012) trained participants on an equal priority dual-task paradigm involving one modality and observed significant transfer effects on another modality only for the dual-task cost but not for the heterogeneity cost, while Bherer et al. (2008) have found significant cross-modal transfer effects in the heterogeneity cost only. The dual-task cost and the heterogeneity cost therefore could reflect different underlying limitations despite being measured within the same equal priority dual-task paradigm.

1.3. The Current Study

We adopted an individual differences approach in the current study to examine to what extent the multitasking costs measured in different paradigms reflect common cognitive limitations. The individual differences approach is popular in psychology and cognition, and has been applied in the field of visual attention (e.g., Huang, Mo, & Li, 2012), face recognition (e.g., Wilhelm et al., 2010), memory (Engle, Tuholski, Laughlin, & Conway, 1999), and executive functions (e.g., Miyake et al., 2000). Specifically, exploratory factor extraction using principal component analyses (PCA)[1] was used to identify the common factors underlying individual differences in multitasking costs measured in different paradigms. Ideally one would adopt a confirmatory approach (using confirmatory factor analyse or structural equation modelling), start with alternative theories of the factor structure of multitasking costs, and design multiple tasks to

[1] See the Method section for rationale behind the use of PCA rather than other exploratory factor analysis methods, and Appendix I on the similar results obtained using the latter method.

measure the hypothesized aspects of multitasking. The executive function work by Friedman, Miyake, and colleagues (Friedman et al., 2006; Miyake et al., 2000) is a well-known example. Nevertheless, in those studies each paradigm provides only one indicator that readily taps on an aspect of executive function, each multitasking paradigms included in our study often involved multiple measures of multitasking costs. The literature so far does not provide a strong a priori hypothesis about the number of multitasking limitations, or whether the limitations would be tied to specific paradigms or to specific indicators within each paradigm. The number of possible a priori models to test in a confirmatory factor analysis would thus be unmanageable. Therefore, an exploratory approach would be more adequate for initial examination of this relatively novel question with much unknown.

In terms of task choice, traditional, laboratory-based concurrent multitasking and task switching paradigms commonly used in the literature were selected, as they tend to offer multitasking measures targeted to more specific process limitations compared with more complex tasks that better mimic daily situations. Six multitasking paradigms with eleven indicators of multitasking costs were used[2]. The PRP paradigm and the equal priority dual-task

[2] Eight multitasking paradigms with 14 multitasking cost indicators were initially identified. We decided to exclude two paradigms after a pilot testing with 20 participants. The continuous tracking – word generation paradigm (Strayer & Johnston, 2001) was discarded due to its lower reliability and the high correlation between tracking errors of the tracking tasks in this paradigm and that in the continuous tracking – working memory span paradigms. An interruption paradigm

paradigm were selected to represent concurrent multitasking situations. Both being concurrent multitasking paradigms, they differ drastically in terms of task priority and definition of multitasking costs. A continuous tracking paradigm, with a pursuit tracking task as the primary task and a working memory span task as the secondary task (Alm & Nilsson, 1995), was included to represent concurrent multitasking situations in a continuous task. For task switching, the typical cued task switching paradigm using one cue for one task, the task switching paradigm with 2:1 mappings between cues and tasks, and the task switching paradigm with problem state requirements (Borst et al., 2010) were selected. To explore the relationship between aspects of multitasking performance and various cognitive abilities, we included four secondary paradigms assessing participants' fluid intelligence, working memory capacity, processing speed, and video game playing ability and experience. These abilities have been associated with multitasking ability in previous studies (Achtman, Green, & Bavelier, 2008; Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Hambrick, Oswald, Darowski, Rench, & Brou, 2010; Konig, Buhner, & Murling, 2005; Colom et al., 2010).

2. Method

(Bai, Jones, Moss, & Doane, 2014) was also included in the pilot study and excluded in the actual experiment due to the low reliability of the interruption and resumption costs.

2.1. Participant

Two hundred and twenty participants with written consent (to achieve a planned subjects-to-variables ratio of 20:1) from The Chinese University of Hong Kong, including 95 males and 125 females were recruited with monetary compensation to participate in the experiment (approved by the Survey and Behavioural Research Ethics Committee). The participants aged between 18 and 31 (*M* = 20.61, *SD* = 2.32). All reported normal or correct-to-normal visual acuity and no perceptual or cognitive disorders.

2.2. Procedure

All participants were tested on six multitasking paradigms and four secondary measurements in the same sequence. The whole experiment lasted for about 4.5 hours and was completed in two sessions. Participants completed multitasking paradigms 1 to 3 in the first session and paradigms 4 to 6 in the second session. The secondary measurement that assessed participants' working memory capacity was obtained in multitasking paradigm 3 – the continuous tracking paradigm. The other three secondary measurements were completed at the end of the first session for most participants except for about 5 who completed them at the beginning of the second session as the first session became too long. Participants received a fixed amount of monetary compensation plus an extra bonus based on their performance in some of the multitasking paradigms.

2.3. Paradigm 1 – Equal Priority Dual-task Paradigm

The equal priority dual-task paradigm was similar to the one used in Experiment 3 of Schumacher et al. (2001). One task was an auditory-vocal (AV) task, in which a low (220 Hz), medium (880 Hz), or high (3520 Hz) tone occurred for 40 ms and participants were required to say "one," "two," or "three," respectively in response. The other task was a visual-manual (VM) task, in which a character string (O--, -O-, or –O) appeared at the center of a computer screen and participants responded on a keyboard with their right ring, index, or middle finger respectively. The number of visual stimuli and manual responses were four in Schumacher et al. (2001) but reduced to be three in the present study as pilot testing found that the VM task with four spatially incompatible stimulus-response mappings appeared to be considerably more difficult than the AV task.

There were two types of trials: (i) single-task trials, in which participants performed only one task - either VM or AV; and (ii) dual-task trials, in which participants responded to both tasks simultaneously. In dual-task trials, three dashes were firstly displayed for 500 ms as a warning signal at the centre of the computer monitor followed by the simultaneous presentation of stimuli of the two tasks. Participants were instructed to respond to the two tasks as accurately

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and fast as possible with equal priorities, and not to constrain the serial order of their responses. From these trial types formed two types of blocks: (i) pure blocks consisting of only trials for a task; and (ii) mixed blocks consisting of single-task trials for both tasks as well as dual-task trials interleaved randomly. The inter-trial interval was 2 seconds in both types of blocks. Participants performed two pure blocks and one mixed block as practice and then four pure blocks (two per task and in an alternating order starting with the AV task) followed by five mixed blocks. Each pure block consisted of 45 homogeneous single-task trials (15 for practice blocks) while each mixed block consisted of 18 dual-task (6 for practice blocks) and 30 single-task trials (15 per task, 10 for practice blocks). Feedback about the accuracy and RT was given after each trial in the practice session, and feedback about the number of correct responses, and mean RTs were given after each block in the test session. At the beginning of each block, participants were told which type the block would be.

A similar reward system as that of Schumacher et al. (2001) was adopted to promote fast and accurate responses as well as equal priority to the two tasks during dual-task trials. Two bonus points were awarded for both dual-task and single-task trials with a correct response and RT that fell below deadlines defined by the 75th percentiles of the raw RT distributions from all prior single-task trials in the mixed blocks including those in the practice session. Incorrect responses were penalized by deducting 1 bonus point. Monetary payoffs were awarded in proportion to the bonus points at the end of the experiment.

For both tasks, the RT and accuracy of each response were recorded. The difference in correct RT between dual-task trials and single-task trials within mixed blocks was defined as the dual-task cost, while the difference in correct RT between the single-task trials in mixed blocks and the single-task trials in pure blocks was defined as the heterogeneity cost. The two multitasking costs were calculated separately for the two tasks as the two tasks involved different perceptual and response modalities.

2.4. Paradigm 2 – The Psychological Refractory Period (PRP) Paradigm

The PRP paradigm was modified based on Experiment 2 of Schumacher et al. (2001). This paradigm used the same two tasks as the equal priority dual-task paradigm and differed in three aspects. Firstly, the PRP paradigm contained only dual-task trials and no single-task trials. Secondly, on each trial, the stimulus for the VM task followed the stimulus for the AV task by a variable stimulus onset asynchrony (SOA) of 50, 150, 250, 500, or 1,000 ms. Thirdly, while being instructed to respond as quickly and accurately as possible to each stimulus, participants were told to treat the AV task as primary and always respond to the AV task first or else both responses were considered incorrect. There was no practice session and participants were required to perform 6 dual-task blocks with 45 trials per block. The various SOAs occurred equally often within each block.

A similar reward system to that of Schumacher et al. (1999) was adopted to encourage participants to complete the primary task (i.e., the AV task) as quickly as possible regardless of SOAs and discourage grouping of responses to the two tasks. Each trial with correct responses was awarded 100 bonus points with 1 point being taken away for every 100 ms of RT. Additionally, an extra 1000 points were awarded for the block in which the mean AV task RT at 50-ms SOA was within 75 ms of the mean AV task RT at 1000-ms SOA. Monetary payoffs were awarded in proportion to the bonus points at the end of the experiment.

For both tasks, the RT and accuracy of each response were recorded. The PRP effect was defined as the difference in correct RT between trials with a 1000-ms SOA and trials with a 50-ms SOA in the VM task. Only trials with the longest and shortest SOA were used to calculate the PRP effect in order to maximize the individual difference which was a common practice in individual differences studies (e.g. Lague-Beauvais, Gagnon, Castonguay, & Bherer; Ruthruff, Van Selst, Johnston, & Remington, 2006; Van Selst, Ruthruff, & Johnston, 1999).

2.5. Paradigm 3 – Continuous Tracking and Working Memory Span Task

The continuous tracking paradigm used the same pursuit tracking task as that of Experiment 2 of Strayer and Johnston (2001), while the secondary task was a working memory span task adopted from Alm and Nilsson (1995). In the tracking task, participants were required to use a mouse to maneuver the cursor aligning it as closely as possible to a target dot that moved in a smooth and continuous yet unpredictable manner. The position of the target dot was updated every 33 ms and determined by the sum of three sine waves (at frequencies of 0.07 Hz, 0.15 Hz, and 0.23 Hz). The target flashed red or green with an equal probability at random intervals ranging from 10 to 20 seconds (M = 15s), and participants had to press the "brake button" – the left button of the mouse – in response to the red flash as fast and accurately as possible.

For the working memory span task, participants listened to sentences recorded earlier by the experimenter. Each sentence contained three to five words and was in the form of "X does Y". For instance: "The boy ate his breakfast" and "The rabbit wrote an article". For each sentence listened, participants had to say to a microphone "yes" if the sentence was sensible (half of them were), and "no" if it was not. In addition, for every five sentences, the experimenter asked participants to recall the last word of each sentence in the order they listened. The sentences were presented to participants in a speed of one per ten seconds and participants had an extra ten seconds to recall the last words after every five sentences. Hence, each session of the working memory span task (5 sentences) required 1 minute to complete.

For the single-task session, there was a 3-minute warm-up block to acquaint participants with the tracking task, followed by two 5- minute testing blocks. Before starting the dual-task session, participants were required to complete a 3-minute practice block for the working memory span task, which also served as the working memory capacity measurement in the present study. Afterwards, participants performed two 5-minute dual-task blocks in which they had to perform the pursuit tracking task and the working memory span task simultaneously.

The root mean square tracking error (RMSTE) in the pursuit tracking task was calculated by taking the root mean square of the deviations of the cursor position from the target position. The RMSTE cost was defined as the difference in RMSTE between single-task blocks and dual-task blocks, and served as the main indicator of the multitasking cost for this paradigm. Working memory capacity (one of the secondary measures) was obtained as the number of correctly recalled last words (in the order they were presented, for correctly judged sentences) in the working memory span task.

2.6. Paradigm 4 – Task-switching Paradigm with 1:1 Cue-Task Mapping

The paradigm used a typical task-cued stimulus-classification procedure (Monsell, 2003; Ophir et al., 2009). At the beginning of each trial, one of the two cues (‘‘NUMBER’’ or ‘‘LETTER’’) was presented for 200 ms, followed by a digit-letter pair (such as ‘‘7b’’ or ‘‘b7’’). If the cue was “NUMBER”, participants should perform the number task – press the ‘F’ button for an odd number and the ‘J’ button for an even number. In contrast, if the cue was “LETTER”, participants should perform the letter task – press the 'F' button for a vowel and the 'J' button for a consonant. The intertrial interval was 950 ms. Participants were instructed to respond to the stimuli as quickly and accurately as possible.

There were four short practice blocks (5 trials per block) at the beginning of the paradigm, including two single-task blocks and two mixed-task blocks. In the test session, participants performed four single-task blocks (letter task first, followed by number task, and so forth) followed by four mixed-task blocks. Each block contained 60 trials. In the mixed blocks, trials were randomly generated with an equal frequency of 1, 2, 3, and 4 same-trial sequences, yielding 40% switch trials (trials with a different task to that of the previous trial) and 60% repeat trials (trials with the same task to that of the previous trial).

Participants' RT and accuracy were recorded. The switch cost was defined as the RT difference between switch trials and repeat trials in the mixed-task blocks while the mixing cost was defined as the RT difference between repeated trials in the mixed-task blocks and single-task trials in the single-task blocks.

2.7. Paradigm 5 – Task-switching Paradigm with 2:1 Cue-Task Mapping

The paradigm, adopted from Mayr and Kliegl (2003), used two cues for each task to indicate which task to perform for each trial, such that in some trials the cue switched but the task repeated, while in other trials both the cue and the task switched. If the task cue, presented 300 ms after the preceding response and lasted for 200 ms until the presentation of the stimulus, was the letter G or S, then participants had to discriminate the colour of an object. If the task cue was the letter B or W, then participants had to discriminate the shape of the object. The object could be a circle, a square, or a triangle of about the same size, and it could appear in green, blue, or red. In response, participants had to press the keys 1, 2, and 3 on the numeric keyboard respectively using their index, middle, or ring finger.

There were two single-task blocks and one mixed-task block with 30 trials each in the practice session. In the test session, eight mixed-task blocks with 90 trials each were presented. Task instructions as well as the stimulus-response mappings were presented at the beginning of each block. Stimuli, tasks, and cues were selected randomly for each trial with a constraint of equal number of the three types of trials (task-switch trials, cue-switch trials, and non-switch trials).

Participants' RT and accuracy were recorded. The task-switch cost was defined as the RT difference between task-switch and the cue-switch trials, while the cue-switch cost was defined as the RT difference between the cue-switch and non-switch trials. Note that the task-switch cost calculated in this paradigm was a different measurement to the switch cost obtained in the previous paradigm.

2.8. Paradigm 6 – Task-switching Paradigm with a Problem State Requirement

This paradigm, adopted from Borst et al. (2010), required participants to switch back and forth between a subtraction task and a text entry task for every response. The subtraction task required participants to solve a 10-digit subtraction problem in a right to left order while the text entry task required participants to enter a 10-letter string letter by letter. The screen was divided into two panels, with the subtraction task shown on the left and the text entry task shown on the right. A trial always started with the subtraction task panel active, i.e., any response would be registered for the subtraction task. After each key response, the panel for the other task would become active, forcing participants to perform another task in the next response. A trial ended when all ten responses were registered for each of the two tasks. The next trial begun after 5 seconds.

There were two conditions: easy and hard. In the easy condition, the subtraction task involved an upper digit that was always larger or equal to the lower digit such that the problem could be solved without borrowing, while the text entry task involved letters presented one by one and participants just needed to press the corresponding button when they saw one letter appear on the screen. Therefore, there was no need to keep any information in memory when switching from one task to another. In the hard condition, the subtraction task required participants to borrow six times out of the ten responses and participants would thus need to keep track of whether a borrowing was in progress. The text entry task involved a 10-letter word that appeared at the beginning of a trial and disappeared on subsequent responses, and participants had to keep track of which letter of the word they were entering for each response. The hard condition therefore was supposed to impose a problem state requirement, i.e., a requirement to keep track of the current status or intermediate solution of a task while switching to another task.

Participants performed four single-task trials and four task-switching trials as practice, and then four test blocks each of which containing nine trials per condition (easy and hard). Trials were grouped into sets each containing three trials of the same condition and the condition sets were randomized within a block with a constraint that the first condition of a block was different from the last condition in the previous block. Each trial started with 200 bonus points, with 10 points awarded for every correct response and 2 points removed for every second spent to respond. During the inter-trial interval, feedback about the number of digits and letters entered correctly in the previous trial was shown to the participants. In order to obtain maximal bonus points, participants had to respond both quickly and accurately. Monetary payoffs were awarded corresponding to the bonus points at the end of the experiment.

Participants' RT and accuracy were recorded and the difference in correct RT between the easy condition and hard condition was calculated to represent the cost of the problem state requirement. A surprising observation was that some participants, immediately after entering a letter for the text entry task in the hard condition, moved their finger to the key on the keyboard corresponding to the next letter, thus avoided the need to keep the next letter in memory while switching to the subtraction task[3]. This observation was confirmed by a virtually non-existent difference in response times between the hard vs. easy conditions in the text entry task (85 ms shorter for the hard than easy condition), compared to 2876 ms longer for the hard than easy condition in the subtraction task. As the problem state requirement for the text entry task no longer existed in the hard condition, the performance difference between the easy and hard conditions for the subtraction task should simply reflect differences in only the subtraction task instead of the interference between the two tasks (i.e. the problem state bottleneck). The critical difference of the hard condition to the easy condition was the additional demand of mental processing in each calculation step: recalling whether there was a borrowing requested by the previous digit, deciding whether borrowing was need for the current digit, and engaging in more complicated calculations when borrowing was needed (e.g. 13 – 7). Therefore, we used for

[3] A difference between the text entry task adopted in Borst et al. (2010) and that in the current study was that Borst et al. (2010) required participants to enter the letters by clicking on an on-screen keypad while participants entered the letters by simply using the keyboard in the current study. Due to this difference, participants in the current study were able to move their fingers to the next letter on the keyboard during the subtraction task in the hard condition. As a result, they could respond very quickly to the text entry task in the next trial.

further analyses the RT difference between the hard and easy conditions only for the subtraction task, and regarded this as the processing demand instead of the problem state cost.

2.9. Secondary Measure 1 – Fluid Intelligence

This Raven's Advanced Progressive Matrices Test (APM; Raven, Court, & Raven, 1985) has been the commonly used test of fluid intelligence. As the full version of APM (36 items) requires about 40-60 minutes to complete, and a short version (12 items) developed by Bors and Stokes (1998) showed a ceiling effect in pilot testing, a speeded version of APM was administrated in the full-scale experiment as a paper and pencil test. Participants were required to perform two instruction items before the actual test. They were told that the Raven's test contained 36 items which were arranged in the order from the simplest to the most difficult and they had only 15 minutes for the test. The number of correctly answered question served as the score of their general intelligence.

2.10. Secondary Measure 2 – Working Memory Span

A variety of complex span tasks including reading-span task, operation-span task, and counting-span task were frequently used for assessing working memory capacity (Engle, 2002). All the complex span tasks require processing and storage at the same time with different span tasks differing in the format of processing and content of storage. In the current study, the 3-minute single-task block of the working memory span task performed in the continuous tracking paradigm was used as the measurement of participants' working memory capacity. This working memory span task can be viewed as a variant of the reading-span task – requiring participants to read a number of sentences while keeping the representations of last words, which has been shown to be an adequate measure of working memory capacity (e.g. Engle et al., 1999). The number of correctly recalled last words in the order they were presented served as the indicator of the working memory (WM) capacity.

2.11. Secondary Measure 3 – Processing Speed

To assess participants' processing speed, the letter comparison task used in Hambrick et al. (2010) was adopted and a symbol comparison task was created additionally. In the test, stimuli were pairs of letters or symbols separated by an underscore (e.g. ȺϬŦ _ ҍ ϬŦ) and participants had to judge whether the pairs of stimuli were the same or different as accurately and fast as possible by putting a tick or a cross respectively in a box next to the stimuli. The processing speed test was again a paper and pencil test and was administrated in four parts (2 for letter comparison and 2 for symbol comparison) with 30 seconds for each part. The score of processing speed was calculated as the number of correctly answered items minus the number of incorrectly answered ones.

2.12. Secondary Measure 4 – Video Game Playing Experience and Skill

Two questions were asked to assess participants' video game playing experience and skill. The first question asked participants to report the number of hours they spent on playing video games per week in the past year. The second question asked participants to rate their video game playing skill compared with others in a 1 to 7 scale (1 = very poor to 7 = very good).

3. Results

Data of 19 participants were discarded as three of them did not complete all the tasks and 16 got an accuracy below 0.85 as well as over 3 standard deviations (SDs) below the average of the remaining participants in at least one of the multitasking paradigms. As a result, data from a total of 201 participants including 84 males and aged from 18 to 31 (M = 20.62, SD = 2.37) were further analyzed. The average accuracy over participants was over 0.95 for all multitasking paradigms. For each paradigm, trials with an incorrect response or an RT that was 3 SDs over the mean correct RT of that participant were discarded.

3.1. Descriptive Statistics, Distributions, and Reliabilities

General performance in different multitasking paradigms was summarized in Table 1, and the descriptive statistics as well as the reliabilities of the multitasking costs and the secondary measures were summarized in Table 2. All multitasking costs were significantly larger than zero, *t*s(200) > 5.6, $p < .001$. Split-half reliabilities of the multitasking costs and the processing speed measure were estimated by calculating the correlations between odd and even trials and adjusted by the Spearman-Brown formula. As shown in Table 2, the reliabilities for all but one measure were higher than 0.70. Normality of the distributions, as shown by skewness and kurtosis, was satisfactory for the different measures, and did not improve much even after natural logarithmic transformations. This supported the use of multitasking costs without transformation for the EFA.

3.2. Correlations among Multitasking Costs

The Pearson product-moment correlation coefficients among the multitasking costs were shown in Fig. 1. The major observation was the moderate correlations existed in some but not all pairs of costs, suggesting that more than one factors would be necessary to account for the individual differences in the costs. In addition, all correlations between the RMSTE cost and other indicator variables were smaller than 0.2. Although it was suggested that low correlations among RT difference measures might simply indicate low reliabilities of the measures (Miller and Ulrich, 2013), it is less likely the case for the low correlations in the current study given the acceptable magnitudes of the reliabilities. The exact reasons for the low correlations are unknown; nevertheless, due to the low correlations, the RMSTE cost was not included in the subsequent EFA.

3.3. Factor Analysis

Kaiser-Meyer-Olkin (KMO) index (0.749) and Barlett's test of sphericity (p<.001) showed that overall the multitasking costs were significantly correlated with each other. Principal component analysis (PCA) was performed for factor extraction, although exploratory factor analysis (EFA) are often preferred due to the latter's consideration of only shared variance among variables and thus better exclusion of variance due to noise (Fabrigar, Wegener, MacCallum, & Strahan, 1999). This is because PCA allowed us to compute factor scores for assessing the correlations of factors with the secondary variables. The computation of factor scores during EFA is generally not recommended due to the factor indeterminacy problem (Velicer & Jackson, 1990). Although Fabrigar et al. (1999) argued that the factor indeterminacy problem was not a problem as one can perform structural equation modeling to examine the correlates between the factors and other variables, this was not preferred in our case as we adopted an exploratory approach in the current study. Still, results of EFA (principal axis factoring) are shown in the Appendix I for readers' information, and they are qualitatively the same as the results of PCA.

Several methods were used to determine the number of factors. The Kaiser's eigenvalue-greater-than-one-rule suggested three factors, explaining 29.81%, 14.60%, and 10.68% of total variance respectively (54.99% combined). Revelle and Rocklin's very simple structure (VSS) test also suggested a 3- factor solution. Parallel analysis (PA), on the contrary, suggested a 2-factor solution, and the scree test favoured both the 2- or 3-factor solution (Fig. 2)[4].

With regard to the inconsistent suggestions, both the 2- and 3-factor solutions were examined. As can be seen in the rotated-structure matrices of the two solutions (Table 3), the

[4] Velicer's minimum average partial test (MAP) was not performed in the current study, as the MAP method showed consistent underestimation of the number of factors when the number of variables per component was small (Zwick & Velicer, 1986).

factor structures were highly similar. The only difference was the further split of Factor 2 of the 2-factor solution into Factors 2 and 3 in the 3-factor solution. The 3-factor solution was preferred for two reasons. Firstly, Confirmatory Factor Analysis (CFA) was performed for the two models (shown in Appendix II) and a Likelihood ratio test was conducted to compare the model fits of the two models. The 3-factor model (χ^2 (32, N = 201) = 53.05) showed a significant better model fit than the 2-factor model (χ^2 (34, N = 201) = 67.23), $\Delta\chi^2$ (2, N = 201) = 14.18, $p < .01$. Secondly, the 3-factor model enabled the discrimination between the cue-switch cost and the task-switch cost. Theoretically these two costs have been attributed to separate stages of task switching (Jost et al., 2008; Mayr & Kliegl, 2003, Schmitz & Voss, 2014). Although, the current study adopted a data-driven approach, we argued that it is not inappropriate to take theoretical viewpoints into consideration when the data-driven approach (e.g. EFA) could not provide a clear solution. Indeed, the cue-switch cost and the task-switch cost did not correlate with each other in the current data, $r(199) = .08$, $p = .29$. The other indicators (e.g., the mixing cost and the switch cost) have been linked to both stages of task switching in the literature, and were indeed double loaded on both Factors 2 and 3. Therefore, subsequent analyses were conducted based on the 3-factor solution.

Factor rotation was performed using direct oblimin – an oblique rotation method – to allow estimations of factor correlations, while Varimax rotation – an orthogonal rotation method

– showed the same factor solutions (i.e., the same factor-variable associations) as the correlations among the three factors were very small (all below < .20). According to the 3-factor solution (Table 3), the dual-task costs, the heterogeneity costs, the PRP effect, and the processing demand mainly loaded on Factor 1; the cue-switch cost and the mixing cost mainly loaded on Factor 2; and the switch cost and the task-switch cost mainly loaded on Factor 3. There were also double-loadings in the 3-factor solution, with small loadings of the heterogeneity cost for the visual-manual task on Factor 3, the PRP effect on Factor 2, the mixing cost on both Factor 1 and Factor 3, and the switch cost on Factor 2.

3.4. Additional Analyses with a Subset of Variables

One potential concern about the current factor solution is whether interdependence of the indicators may have biased the results. The computation of four pairs of indicators (the two dual-task costs and the two heterogeneity costs, the switch cost and the mixing cost, the cue-switch cost and the task-switch cost) involved one common condition, which may have created dependencies between the indicators resulting in the current factor structure. Specifically, the dual-task costs (VM and AV) and the heterogeneity costs (VM and AV) both involved the heterogeneous single-task trials as the baseline condition, and the costs did load on Factor 1. The switch cost and mixing cost both involved the single trials in the 1:1 cue-task mapping paradigm as the baseline condition, although this is not as much an issue as the costs loaded on different factors (Factors 2 and 3 respectively). Similarly, although the cue-switch cost and the task-switch cost both involved single trials in the 2:1 cue-task mapping paradigm as the baseline condition, the two costs in fact loaded on different factors (Factors 2 and 3 respectively). Still it would be important to check if a similar factor structure would be obtained when the computation of the indicators did not involve overlapping baseline variables.

Additional analyses were therefore performed by including only one indicator of each of the four pairs described in the previous paragraph. For the equal-priority dual-task paradigm, the dual-task costs (VM and AV) were included and the heterogeneity costs (VM and AV) were dropped, as the former are the more representative and commonly used indicators of multitasking costs in the literature. For the task-switching paradigm with 1:1 cue-task mapping, the switch cost was included and the mixing cost dropped for the same reason. For the task-switching paradigm with 2:1 cue-task mapping, the cue-switch cost and the task-switch cost were supposed to represent two distinct cognitive stages of task switching (Jost et al., 2008; Mayr & Kliegl, 2003), and it is relatively less clear which one is more representative as a multitasking cost. As a result, two additional PCAs were performed with one including only the cue-switch cost and the other one including only the task-switch cost.

The factor solutions of the additional PCAs are shown in Appendix III. It should be noted that, due to the exclusion of the mixing cost and one of the cue- and task-switch costs, there would not be sufficient indicators to dissociate Factors 2 and 3. The critical question here was whether response selection would still emerge as a multitasking limitation separate from the limitation in task information retrieval and maintenance / task-set reconfiguration without the issue of the indicator interdependencies. Indeed this was the case. A two-factor solution was obtained, with the dual-task costs, the PRP effect, and the PD cost again loaded mainly on Factor 1 and the switch costs loaded mainly on Factor 2. Therefore, the 3-factor solution obtained in the original analysis with the full set of indicators was unlikely the result of the potential interdependence of the indicators.

3.5. Further Exploratory Analyses of the Relationships with Secondary Measures and Gender

Factor scores were computed for each factor as the sum of all multitasking costs weighted by the factor loadings obtained from PCA. Correlations between the factor scores and the secondary measures were shown in Table 4. Several observations were worth noting. First, the correlations were mostly negative as expected, which means the better one performed in secondary measures, the smaller were one's multitasking costs. Second, the correlations were small (.33 or below in magnitude), suggesting that multitasking ability cannot be fully captured by these common measures of fluid intelligence and executive functions. Third, Factor 1 correlated significantly with processing speed and video game playing experience and competence, while factors 2 and 3 were relatively more related to working memory capacity. How this relates to the interpretation of the factors will be considered more in the discussion section.

Independent samples *t*-tests were performed to examine whether there were gender differences (84 males vs. 117 females) in the factor scores and secondary measures (Table 5). Males on average showed a smaller Factor 1 score, i.e., a smaller response selection cost, than females, although males also reported spending more time and being more skilful in video game playing. Regression analyses showed that gender significantly explained 6.5% of the variance of Factor 1 ($R^2 = .065$, $p < .001$), and the percentage dropped to 2.8% but were still significant ($pr = .172$, $\Delta R^2 = .028$, $F(1,197) = 6.04$, $p = .015$) after controlling for video game experience and skill. This means that the smaller multitasking cost indicated by Factor 1 in males than females can be partially but not completely explained by males spending more time and being better in video game playing. On the other end, females showed a significantly larger working memory capacity than males, and a trend of smaller multitasking costs than males as in the scores of Factor 2 and Factor 3. Regression analyses showed that gender explained 0.7% of the variance of Factor 2 ($R^2 = .007$, $p = .244$) and 0.6% of the variance of Factor 3 ($R^2 = .006$, $p = .279$), and the percentage raised to 1.5% for Factor 2 ($pr = -.124$, $\Delta R^2 = .015$, $F(1,197) = 3.07$, $p = .081$) and 1.7% for

Factor 3 (pr = -.131, ΔR^2 = .017, $F(1,197)$ = 3.07, p = .065) after controlling for video game experience and skill. This again was consistent with the finding of the negative correlation between working memory capacity and Factors 2 and 3. Overall, the results suggest that gender difference may manifest itself differently in different aspects of multitasking.

4. Discussion

The current study represents the first empirical attempt to reveal the common and distinct limitations underlying various multitasking performance measures in different paradigms. Results showed that there was not one general limitation in information processing applicable to various multitasking situations. Instead, three sources of limitations of information processing were necessary to account for individual differences in multitasking performance. As discussed below, the three factors were interpreted as limitations in response selection, retrieval and maintenance of task information, and task-set reconfiguration respectively. Importantly these factors did not map simply onto specific paradigms but instead onto specific indicators across different paradigms. The contributions of the three factors to performance on the tasks are shown in Table 6.

4.1. Interpretation of the Three Factors

The heavy loadings of the dual-task costs and the PRP effect on Factor 1 suggest that this factor is related to the response selection process (Pashler 1994; Pashler & Johnston, 1989) which is the process of selecting appropriate actions or responses based on the task requirements or the stimulus-response mappings. We hence interpreted Factor 1 as reflecting limitations in *response selection.* In addition, we suggested that the response selection limitation does not necessarily involve making explicit responses. If a task requires more than one mental step to achieve the final response (e.g. mental solving an algebra problem like 3x + 3 = 9), the mental processes that generate intermediate mental representations (e.g. 3x = 6) can also be viewed as a response selection process.

The heterogeneity costs, which are not clearly related to the response selection bottleneck, also loaded heavily on Factor 1. As the heterogeneity cost is calculated as the RT differences between single-task trials in mixed-task blocks and single-task blocks, some may argue that it should reflect the same processing limitation as the mixing cost – the simultaneous maintenance of two task-sets rather than one. It should be noted that, however, the mixed-task blocks of the two paradigms were not identical. The dual-task blocks in the equal priority dual-task paradigm contained not only two tasks, but also two types of trials: dual-task trials and heterogeneous single-task trials. Participants may have to decide which type of trials it is and how many responses they need to make at the beginning of heterogeneous trials. This intermediate mental process can be viewed as a response selection process that would better prepare for the later execution of the explicit response(s). The high loading of the heterogeneity costs on Factor 1 would be consistent with the view that additional response selection process was involved in the heterogeneous single-task trials.

The processing demand also loaded on Factor 1. The processing demand (2875 ms) was much larger compared to other multitasking costs (ranging from 116 ms to 422 ms). We believe that the major source of the processing demand concerns the steps of mental calculation. An easy trial of the subtraction task only required subtraction of a smaller number from a larger number (e.g., subtract 3 from 7, 7 – 3 = 4). A hard trial, however, involved subtraction of a smaller number from a larger number sometimes, and the reverse at other times. As borrowing was required only in the latter trials, each hard trial involved more mental calculation steps and thus imposed a larger demand on selecting the final response. As a result, it is reasonable that the processing demand mainly loaded on Factor 1.

Factor 2 can be interpreted as limitations in *retrieval and maintenance of task information*. The indicator variable with the highest factor loading on Factor 2 was the cue-switch cost which implies that Factor 2 is highly likely to be related to the first stage of task switching – the cue-driven stage of retrieving the task-set from the long-term memory onto the working memory (Mayr & Kliegl, 2003)[5]. The loading of the switch cost on Factor 2 was consistent with this interpretation as the switch cost should include costs in all stages of task switching process.

The considerable loading of the mixing cost on Factor 2 further suggested that Factor 2 related also to the maintenance of task information in working memory. The critical difference between the trials in the single task blocks and the repeated trials in the mixed task blocks is that for the latter the participants performed one of two possible tasks and so needed to maintain additional task information (Mayr, 2003). The mixing cost was also suggested to reflect an additional process in resolving stimulus ambiguity (Rubin & Meiran, 2005) which may be more related to the response selection process based on the stimulus-response mapping. It is also possible that part of the mixing cost reflects the task-set reconfiguration process since participants did not know whether they are going to perform a repeated or switch trials in the mixed-task blocks. Therefore, the task-set of the repeated trial may not be as well prepared as that in the single-task trials. The results that the mixing cost loaded on all the three factors considerably suggests that the mixing cost may not reflect a pure processing limitation. Nevertheless, the highest loading on Factor 2 suggests a relatively stronger relationship of the mixing cost to the processing limitation retrieval and maintenance of task information.

An interesting and surprising finding is that, the PRP effect loaded considerably on Factor 2, but the equal-priority dual-task costs did not. There have been debates on whether the PRP effect is caused by a structural bottleneck in response selection or a strategic deferment of the second response. The strategic deferment account of the PRP effect was less adopted by researchers because most training studies suggested that an intact bottleneck remained even after training (e.g. Ruthruff et al., 2006). Although rarely suggested, another possibility is that the PRP effect is caused by both the structural bottleneck and strategic deferment. If this is the case, the loadings of the PRP effect on both Factors 1 and 2 become sensible. Factor 1 concerns the response selection bottleneck; Factor 2 concerns retrieval and maintenance of task information and should be engaged by a deferment strategy that requires keeping the response to the secondary task in working memory (Meyer and Kieras, 1997). Unlike in the PRP paradigm, this strategic component was eliminated in the equal priority dual-task paradigm in which participants were asked to give equal priority to both tasks. Therefore, only the PRP effect but not the two equal priority dual-task costs loaded on Factor 2.

Factor 3 can be interpreted as limitations in *task-set reconfiguration*. The indicator variable with the highest factor loading on Factor 3 was the task-switch cost which implies that Factor 3 is more likely to be related to the second stage of task switching – the reconfiguration of the cognitive system for a different task-set. The loading of switch cost on Factor 3 provided a good verification for this interpretation. The low correlation between the cue-switch and task-switch costs, $r(199) = .08$, $p = .29$, suggests that they indeed indicate two distinct cognitive stages of task switching. The loading of the switch cost on Factor 3 was higher than its loading on Factor 2, further suggesting that a larger part of task switch cost in our study should be attributed to the task-set reconfiguration process.

It seems to be strange that the heterogeneity cost of the VM task had a significant loading on Factor 3 while the heterogeneity cost of the AV task did not. It should be noted, however, that the heterogeneous single-task trials can be either repeated trials or switch trials. If a heterogeneous single-task trial is a switch trial, the heterogeneity cost contains also a component of task switching. In the current study, 75% of heterogeneous single-task trials of the VM task (75 trials in total) were switch trials, and 67% of heterogeneous single-task trials of the AV task (76 trials in total) were switch trials. The heterogeneity cost of the VM task (161 ms) was significantly larger than that of the AV task (116 ms), $t = 5.89$, $p < .001$, and this extra cost could be related to the higher proportion of switch trials for the heterogeneous single-task trials of the VM task. This may explain why the heterogeneity cost of the VM task had a larger loading on Factor 3.

4.2. The Multifaceted Nature of Multitasking Limitations

The identification of multiple limitations underlying multitasking performance helps resolve inconsistent findings concerning gender differences in multitasking ability. Previous studies used a single task and indicator to infer a general multitasking advantage of one group over the other (e.g., Colom et al., 2010; Stoet et al., 2013). However, our findings suggest that males and females are superior in distinct aspects of multitasking: Males showed significantly smaller limitations in terms of response selection (Factor 1) than females, while females showed numerically smaller limitations than males in terms of retrieval and maintenance of task information and task-set reconfiguration (Factors 2 and 3). This may partly explain why males in Colom et al. (2010) performed better in a concurrent multitasking paradigm, where response selection tends to be more involved, whereas females in Stoet et al. (2013) performed better in a task switching paradigm, where retrieval and maintenance of task information and task-set reconfiguration are more relevant. It would thus be more comprehensive and insightful if future studies comparing different populations can consider separate aspects of multitasking ability. Apart from gender, comparison between age groups may also have important implications. There were findings of age-related decrements in multitasking performance (e.g. Kramer, Larish, & Strayer, 1995), and it is meaningful to identify which aspects of multitasking have the largest decrement caused by aging.

It may be tempting to categorize Factor 1 as purely a concurrent multitasking limitation and Factors 2 and 3 as purely task switching limitations, since all costs measured in the concurrent multitasking paradigms were highly loaded on Factor 1 and the two stages of task switching were obviously represented by Factor 2 and Factor 3. Nevertheless, we argue that it is not appropriate to categorize multitasking limitations in this dichotomous way. For one, the performance difference between the hard and easy versions of the task switching paradigm (the processing demand, Table 3) was also loaded on Factor 1. This is why it is better to interpret Factor 1 as a response selection limitation that is not limited to concurrent multitasking paradigms. For another, the PRP effect was not only loaded on Factor 1 but also on Factor 2, as there was a processing limitation of retrieval and maintenance of the second response in the concurrent multitasking situation where the PRP was measured. Therefore, which processing limitation(s) are involved depends not only on the coarse categorization of the task (dual-task or task switching), but also on the specific requirements and the way in which each multitasking cost is calculated.

The double loadings discussed above can perhaps account for the pattern of transfer in previous multitasking training studies. For example, Strobach et al. (2012) found that the effects of training in an equal priority dual-task paradigm transferred to better performance in a task-switching paradigm in terms of the mixing cost but not the switch cost. Consistently, in the current study, while the mixing cost was mainly loaded on Factor 2, it also was moderately loaded on Factor 1. The loading (0.253) was higher compared with those of the cue-switch cost (-0.056), the task-switch cost (-0.033), and the switch cost (0.170), suggesting that the mixing cost shares more variance with costs measured in the equal priority dual-task paradigms than the switch cost (Table 3). Another example is the inconsistent cross-modal transfer effects on the heterogeneity cost across studies (Bherer el al., 2008; Lussier et al., 2012). As shown in our findings, the heterogeneity cost was loaded on both Factors 1 and 3. It may thus be difficult to compare the findings concerning heterogeneity costs in different studies and they may be affected by different combinations of multitasking limitations depending on task parameters such as the proportion of switch trials in the dual-task blocks. An obvious implication for future training studies is the need to develop a multitasking training regimen incorporating training on all the three underlying processing limitations of multitasking to maximize training effects and the transfer to novel situations.

The three multitasking limitations were significantly correlated with the secondary measures in our study. Yet the correlation coefficients were all small (all *r*s <.30), suggesting that multitasking skills are not reducible to typical cognitive measures like intelligence, working memory, or processing speed, or a single habit like video game playing. The correlations between Factor 1, processing speed and video game playing are sensible. Behavioral and neuroimaging studies have shown a connection between information processing speed and multitasking performance (Dux et al., 2009; Hambrick et al., 2010). Video game playing, especially those involving actions and real-time strategies, involves lots of response selection processes. The correlations between working memory capacity and Factors 2 and 3 were also expected, as Factor 2 involves retrieval and maintenance of task information and Factor 3 involves the task-set reconfiguration processing that likely occurs in working memory. Note that the secondary constructs were measured by a single indicator and they may contain certain amount of task-specific variance. As the secondary analysis was exploratory in nature in the current study, future studies should more systematically examine the relationship between the different multitasking abilities and other cognitive constructs including established aspects of executive functions, such as mental set shifting, working memory updating, and inhibition (Miyake et al., 2000). While retrieval and maintenance of task information and task-set reconfiguration may represent different components under mental set shifting, response selection could reflect an ability not accounted for by Miyake et al.'s (2000) model. In fact, Miyake et al. (2000) found in their study that dual-task performance was not related to any of the three components of executive functions they proposed.

One may wonder if the factors identified in the current study were confounded with session. The equal-priority dual-task and the PRP paradigms were introduced in the first session and the switching paradigms were introduced in the second session. And apparently many indicators of paradigms introduced in the first session seemed to load on Factor 1 while those in the second session on Factors 2 and 3. However, three aspects of our results showed that session was unlikely the main cause of our factor-analytic results. First, there were a number of cross-session loadings: (1) the HG Cost (VM) loaded on Factor 3, (2) the PRP effect loaded on Factor 2, (3) the processing demand loaded on Factor 1, (4) the mixing cost loaded on Factor 1. Among the four cross-session loadings, processing demand highly loaded on Factor 1 (.533) but did not load on Factor 2 and 3 (.136 and -.069 respectively). Second, the multitasking cost measured in the continuous tracking paradigm (in session 1) did not correlate at all with the costs measured in the paradigms in session 1. Third, as shown in Table 4, among the three performance-based secondary measures (all obtained in session 1), processing speed was significantly correlated to all three factors while Raven's test and WM capacity were only correlated with Factors 2 and/or 3 but not Factor 1.

One intriguing question concerns whether three limitations are sufficient to account for multitasking performance in a wider range of situations. It is unfortunate that we could not include interruption paradigms (Bai et al., 2014; Trafton, Altmann, Brock, & Mintz, 2003) in the current study given our failure during pilot studies in establishing a reliable multitasking cost measures in this type of paradigms. Besides, we did not include in the current study paradigms that emphasize self-initiated task switching (e.g.,Reissland & Manzey, 2016) that allows more strategic planning. Conclusions on the number of limitations underlying multitasking performance as well as their relationship with executive functions and other cognitive abilities could therefore differ when a more comprehensive set of multitasking paradigms are included in future studies.

4.3. Conclusion

Overall, we found in the current study separable cognitive limitations underlying multitasking performance in different situations. This forms the basis for future incorporation of multitasking limitations into existing theories and models of executive functions and cognitive control. The findings help resolve inconsistent results between studies as a result of using different and/or impure paradigms to compare multitasking abilities between different populations. The findings are also useful for the development of comprehensive training protocols covering different aspects of multitasking limitations. In future, with better understanding of the structure of limitations underlying multitasking performance and more reliable measures of multitasking costs developed, it would be feasible to access the profile of multitasking ability and thus provide personalized recommendations for individuals.

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Table 1 (on next page)

Average performance for different multitasking paradigms

Table 1

Average performance for different multitasking paradigms (RT in msec for all tasks except for RMSTE in pixels for the continuous tracking *paradigm)*

Paradigm	**Trial type (Task)**	**Mean**	***SD***
Equal Priority Dual-task paradigm	Dual-task trial (AV)	927.8	257.7
	Heterogeneous single-task trial (AV)	601.4	133.0
	Homogeneous single-task trial (AV)	484.9	101.8
	Dual-task trial (VM)	1019	372.6
	Heterogeneous single-task trial (VM)	741.0	198.0
	Homogeneous single-task trial (VM)	580.0	137.4
The PRP paradigm	VM task 50ms SOA trial	1067	334.8
	VM task 1000ms SOA trial	645.5	211.5
Continuous tracking paradigm	RMSTE in dual task condition	31.99	13.32
	RMSTE in single task condition	28.01	10.66
Task-switching paradigm with 1:1 cue-task mapping	Switch trial	877.9	253.9
	Repeated trial (mixed task block)	766.8	194.1
	Single trial (single task block)	597.0	96.02
Task-switching paradigm with 2:1 cue-task mapping	Task-switch trial	1517	421.0
	Cue-switch trial	1257	341.0
	Non-switch trial	950.2	252.4
Task-switching paradigm with a problem state requirement	Subtraction task trials (hard condition)	4098	1292
	Subtraction task trials (easy condition)	1222	316.5

Table 2 (on next page)

Descriptive statistics and reliabilities of the multitasking costs and the secondary measures

Table 2

Descriptive statistics and reliabilities of the multitasking costs and the secondary measures

Paradigm	**Variables**	**Mean [95% CI]**	***SD***	**Skew**	**Kurtosis**	**Reliability**
Equal Priority Dual-task paradigm	Dual-task cost (AV)	326.4 [303.0, 349.8]	168.2	1.002	1.050	0.90
	Dual-task cost (VM)	277.9 [248.0, 307.7]	214.8	-.126	-.721	0.93
	Heterogeneity cost (AV)	116.5 [105.5, 127.5]	78.78	.655	1.190	0.84
	Heterogeneity cost (VM)	161.0 [144.5, 177.5]	118.4	.644	.679	0.85
The PRP paradigm	PRP effect	422.0 [398.1, 445.8]	171.6	.060	-.726	0.87
Continuous tracking paradigm	RMSTE cost	3.980 [2.590, 5.360]	9.950	-0.068	6.215	0.71
Task-switching paradigm with 1:1 cue-task mapping	Switch cost	111.1 [96.48, 125.6]	104.9	1.385	2.679	0.65
	Mixing cost	169.8 [151.2, 188.4]	133.7	1.056	.989	0.93
Task-switching paradigm with 2:1 cue-task mapping	Cue-switch cost	306.6 [282.4, 330.8]	173.9	.933	.985	0.79
	Task-switch cost	259.7 [234.9, 284.5]	178.2	1.370	3.833	0.71
Task-switching paradigm with a problem state requirement	Processing demand (Subtraction)	2876 [2723, 3029]	1099	.597	.948	0.95
APM test	Raven's test score	22.34 [21.80, 22.87]	3.840	-0.730	1.123	Nil
Processing speed test	Processing speed score	26.00 [25.42, 26.58]	4.160	0.195	-0.178	0.90
Video Game Playing Experience and Skill	Video game playing hours	6.080 [4.790, 7.370]	9.260	3.817	22.31	Nil
	Video game playing rating	3.810 [3.650, 3.960]	1.120	-0.210	-0.668	Nil
Working memory span task	WM capacity	10.77 [10.45, 11.09]	2.300	-0.164	-0.392	Nil

Table 3(on next page)

Rotated structure matrix of the 3-factor and 2-factor solution with the direct oblimin method

Table 3

Rotated structure matrix of the 3-factor and 2-factor solution with the direct oblimin method

		Three-factor solution			Two-factor solution	
Paradigm	**Measure**	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 1**	**Factor 2**
1	HG Cost (VM)	**.718**	-.053	**.338**	**.726**	.153
	HG Cost (AV)	**.697**	.013	.144	**.703** **.699**	.085
2	The PRP effect	**.688**	**.420**	.041	**.682**	**.320**
1	Dual-task cost (VM)	**.681**	.144	.029	**.679**	.111
	Dual-task cost (AV)	**.585**	.191	.263	**.588**	.288
6	PD (subtraction)	**.533**	.136	-.069	**.528**	.049
5	Cue-switch cost	.042	**.867**	.094	.033	**.686**
4	Mixing cost	**.344**	**.696**	**.321**	**.343**	**.693**
5	Task-switch cost	.046	.067	**.873**	.066	**.573**
4	Switch cost	.259	**.386**	**.663**	.270	**.675**

Note. The variables were sorted by their values of factor loadings and the factor loadings larger than 0.3 are presented in boldface. Paradigm 1 = Equal Priority Dual-task paradigm, HG cost = Heterogeneity cost, Paradigm 2 = The PRP paradigm, Paradigm 4 = Task-switching paradigm with 1:1 cue-task mapping, Paradigm 5 = Task-switching paradigm with 2:1 cue-task mapping, Paradigm 6 = Task-switching paradigm with a problem state requirement, PD = processing demand.

Table 4 (on next page)

Correlations between the three common factors and secondary measures

Table 4

Correlations between the three common factors and secondary measures

	Factor 1		Factor 2		Factor 3	
	r	*p*-value	*r*	*p*-value	*r*	*p*-value
Raven's test	-0.121	.088	**-0.156**	**.027**	-0.032	.657
Processing speed	**-0.328**	**<.001**	**-0.277**	**<.001**	**-0.145**	**.039**
Video game experience	**-0.180**	**.010**	0.021	.767	-0.035	.620
Video game skill	**-0.221**	**.002**	**-0.156**	**.027**	-0.138	.051
WM capacity	-0.100	.158	**-0.220**	**.002**	**-0.168**	**.017**

Note. Significant correlations are presented in boldface.

Table 5(on next page)

Results of gender differences in multitasking factors and secondary measures

Table 5

Results of gender differences in multitasking factors and secondary measures

	Males	**Females**	***t***	***p*-value**	***d***
Age	20.54 [20.06, 21.02]	20.68 [20.23, 21.14]	-0.44	.664	0.06
Raven's test	22.50 [21.75, 23.25]	22.22 [21.47, 22.98]	0.51	.614	0.07
PS score	25.97 [24.97, 26.98]	26.02 [25.32, 26.71]	-0.08	.939	0.01
VG hours	10.02 [7.51, 12.53]	3.25 [2.20, 4.30]	**5.46**	**<.001**	0.78
VG rating	4.21 [4.01, 4.41]	3.52 [3.30, 3.73]	**4.51**	**<.001**	0.64
WM capacity	10.27 [9.79, 10.76]	11.12 [10.70, 11.54]	**-2.60**	**.010**	0.37
Factor 1	-0.30 [-0.50, -0.10]	0.22 [0.03, 0.40]	**-3.72**	**<.001**	0.53
Factor 2	0.10 [-0.14, 0.33]	-0.07 [-0.24, 0.10]	1.17	.244	0.17
Factor 3	0.09 [-0.14, 0.32]	-0.06 [-0.24, 0.11]	1.09	.279	0.16

Note. Values in the parentheses represent the 95% confidence intervals. Significant *t*-values are presented in boldface.

Table 6(on next page)

Contributions of the three factors

Table 6

Contributions of the three factors (Response selection, Retrieval and maintenance of task information, and Task-set reconfiguration) to various multitasking costs.

Paradigm	**Measure**	**Factor Contribution**
1	Dual-task cost	**Response selection: Selecting more than one response concurrently**
	Heterogeneity cost	**Response selection: Deciding how many responses to make for the heterogeneous single-task trial**
		Task-set reconfiguration: Reconfiguring the cognitive system for a new task when a heterogeneous single-task trials was also a switch trial
2	The PRP effect	**Response selection: Selecting more than one response concurrently**
		Retrieval and maintenance of task information: Maintaining the secondary task response in working memory until after responding to the primary task
4	Switch cost	**Task-set reconfiguration: Reconfiguring the cognitive system for a new task**
		Retrieval and maintenance of task information: Retrieving the task-set from long-term memory onto working memory
	Mixing cost	**Retrieval and maintenance of task information: Maintaining the task-set in working memory**
		Response selection: Resolving stimulus ambiguity and selecting the correct response
		Task-set reconfiguration: Reconfiguring the cognitive system for the task as the task is unknown for the repeated trials

5	Cue-switch cost	**Retrieval and maintenance of task information: Retrieving the task-set from long-term memory onto working memory**
	Task-switch cost	**Task-set reconfiguration: Reconfiguring the cognitive system for a new task**
6	Processing demand	**Response selection: Engaging in more calculation steps on the way to selecting a response**

Note. For measures loading on multiple factors, the factor with a higher loading is listed first and presented boldface. Paradigm 1 = Equal Priority Dual-task paradigm, Paradigm 2 = The PRP paradigm, Paradigm 4 = Task-switching paradigm with 1:1 cue-task mapping, Paradigm 5 = Task-switching paradigm with 2:1 cue-task mapping, Paradigm 6 = Task-switching paradigm with a problem state requirement.

Figure 1

Correlation Matrix

A matrix of the pair-wise Pearson product-moment correlation coefficients among the multitasking costs. Task-switching_PS_requirement = Task-switching paradigm with a problem state requirement. PD = Processing demand. The cells were filled with black colors of different saturation directly proportional to the magnitude of the correlation coefficients.

Paradigm	Measure	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
Equal priority Dual-task paradigm	V1. Dual-task cost (AV)	1										
	V2. Dual-task cost (VM)	.27	1									
	V3. Heterogeneity cost (AV)	.35	.29	1								
	V4. Heterogeneity cost (VM)	.32	.37	.47	1							
The PRP paradigm	V5. The PRP effect	.37	.41	.34	.31	1						
Simulated driving paradigm	V6. RMSTE cost	-.02	.05	.13	.10	.03	1					
Task-switching paradigm with 1:1 cue-task mapping	V7. Switch cost	.22	.21	.11	.20	.18	.08	1				
	V8. Mixing cost	.17	.17	.24	.24	.35	-.15	.27	1			
Task-switching paradigm with 2:1 cue-task mapping	V9. Cue-switch cost	.14	.03	-.00	-.03	.17	-.03	.25	.38	1		
	V10. Task-switch cost	.12	-.00	.03	.16	.07	.02	.33	.21	.08	1	
Task-switching_PS_requirement	V11. PD (Subtraction)	.15	.28	.20	.28	.30	.04	.14	.09	.06	.00	1

Figure 2

The scree plot of the EFA.