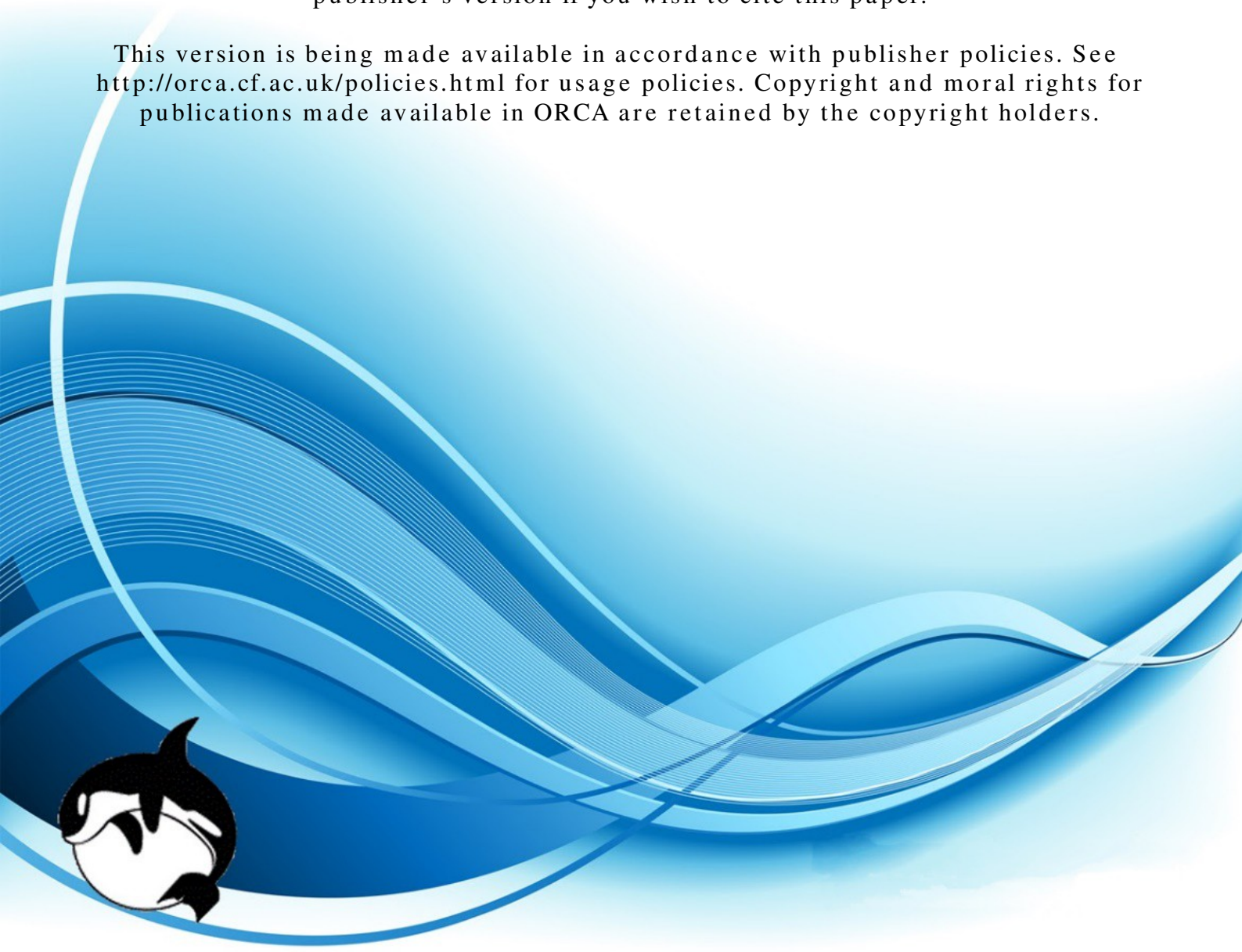

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Co-existing, contradictory working memory models are ready for progressive refinement: Reply to Logie

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Commenting on our paper *Sensory-motor integration and brain lesions: Progress toward explaining domain-specific phenomena within domain-general working memory* (Morey, Rhodes, & Cowan, 2019), Logie (2019) endorses a utilitarian view of science, re-iterates arguments for the multiple-component framework with minimal consideration of its plausible competitor (sensory-motor integration, Buchsbaum & D'Esposito, 2019), and implies throughout that our endeavor to compare the respective merits of the multiple-component and sensory-motor explanations for selective impairment on aural-verbal serial recall tasks was an exercise in motivated reasoning, not an earnest attempt to fully consider this evidence and allow it to refine our views. We first respond to Logie's critique of our use of recognition data available from some patients, then consider the merits of striving to refine models and the evident worth of adversarial discussion.

Logie is quick to dismiss our discussion of data from whole-sequence recognition tasks (p. 167), but in some respects he is mistaken. First, he claims that considering recognition evidence from Basso, Spinnler, Vallar, and Zanobio (1982) and Warrington, Logue, and Pratt (1971) would have changed our interpretation. Logie appears to be referring to the "recognition of letter strings" task from Basso et al., which is not clearly comparable to the whole-sequence recognition data we considered. First, it is unclear how many response options there were (some text is consistent with two, other text implies variation); knowing this is essential for modelling guessing. Second, the text implies that more than one item changed in the "change" options (i.e., "a number of odd letters", "four odd letters"). Finally, Table 3 (p. 267) indicates that participants responded by pointing to an option – it is unclear how this worked in the aural condition, which is the one we would have considered. For these

reasons, we do not know that these data are comparable with the other examples. In Warrington et al., numbers correct are given for only strings of 4 items (p. 383) for JB and WH in addition to KF (who we already included). We might have considered these two additional data points. Logie suggests that doing so would change our story, because "none of those patients showed better recognition than recall" (p. 167). However, comparing recognition and recall data (see Table 4, p. 383, letters with four items per string), KF achieves 72.5% correct on the recognition-based sequence matching task and 10% correct on the recall task, JB achieves 90% correct via recognition and 10% via recall, and WH achieves 75% correct via recognition and 3% correct via recall. These data from JB and WH show the same pattern as the more comprehensive data from comparable patients that we analyzed, and are therefore perfectly consistent with our argument that these patients might have remembered more than their recall scores suggested. Finally, Logie argues that our presentation of the recognition with the recall data in Figure 1 was misleading because in the recognition tasks, participants might have performed better due to guessing. This is why we also included estimates of the same patients' capacity (k). The methods we used to estimate capacity include assumptions about guessing appropriate to each kind of task.

Where does this leave us in evaluating these sequence-matching data? We ultimately did not argue that these data falsify the multiple-component account of these patients' performance. These sequence-matching tasks do not impose identical demands as serial recall tasks – for instance, they might be accomplished with item memory alone, given that the foils include new words. Moreover, they do not require response production. Nonetheless, they arguably require brief memory, as comparable tasks used to investigate visual short-term memory do. We raised this point in our original paper (Morey et al., 2019), suggesting that these matching tasks could be interpreted differently than originally intended, and we argued that they merited further consideration. Other techniques have been applied to measuring

memory without overt recall in these cases, such as part-reporting (Warrington & Shallice, 1969) and missing scan (Shallice & Warrington, 1970), with varying outcomes: judging memory from either of these tasks indeed suggests a deficit. We suspect that comprehensively analyzing the perceptual, cognitive, and motor requirements of each task (which are not necessarily identical) would reveal useful detail about which processes may lead to errors. This ambiguity leaves open the possibility that the deficits observed in these patients are not attributable to storage per se.

Logie argues that knowledge accumulation is best served by seeking utility, contending that the multiple-component approach has been useful to patients with selective deficits, and further questions the worth of "attempting to test whether one theory is correct and others are not" (p. 164). While we agree accumulating knowledge should prove beneficial, this should occur because we are articulating an accurate and increasingly precise description of how the mind works, which naturally entails excluding alternatives. A precise description of temporary maintenance must eventually prove useful in unimagined ways. There are indeed multiple models of working memory (see Cowan, 2017) and multiple interpretations of neuropsychological cases of aural-verbal immediate recall deficits (e.g., Buchsbaum & D'Esposito, 2019; Caplan, Waters, & Howard, 2012; Shallice & Papagno, 2019). Some models of working memory make assumptions contradictory with those of other models. These tentatively co-exist while evidence accumulates, but this does not imply that both interpretations are correct. As evidence accumulates, models that propose broad, vague outlines are gradually replaced by models with increased specificity. Sometimes initial ideas will be tweaked slightly, and sometimes they will be abandoned. An increasingly specific theoretical description will grow more useful to anyone aiming to apply the theory to a practical problem; for instance, it will better identify boundary conditions missed by the

broad-strokes view. The field of working memory is reaching a point of maturity that affords this theoretical refinement (Oberauer et al., 2018).

Although the sensory-motor integration account (e.g., Buchsbaum & D'Esposito, 2019) is disputed (Shallice & Papagno, 2019), we are not convinced that it has been ruled out. Both proponents and critics concur that aural-verbal short-term memory deficits often co-occur with disruption of speech perception, production, or both. Shallice and Papagno argue that the preponderance of evidence is most consistent with the possibility that patients experience deficits to a phonological input buffer, a phonological output buffer, or both. If recent memory is a consequence of sensory-motor integration, rather than a distinct system, then pure cases of recent memory impairment without attendant speech perception or production difficulties are indeed difficult to explain. Buchsbaum and D'Esposito surmise that the individuals presenting with pure storage impairments possessed an unusual facility to recover their related speech functions, though in a way that does not support normal memory. Supporting this contention, lesions encompass widespread regions that typically subserve non-memory functions even in these patients, consistent with the assumption that initial language deficits recovered with some functional reorganization. The inability to identify a discrete region exclusively sustaining phonological short-term storage clearly presents a difficulty for the buffer perspective (see Buchsbaum & D'Esposito, 2008). New evidence will surely bolster one of these accounts, but we maintain that sensory-motor integration remains plausible, and must therefore be considered in developing working memory theory.

In arguing that we must retain specialized short-term stores in part because they provide a convenient explanation for patients, Logie conflates evidence and interpretation. We consider the main evidential pattern shown by these patients – that recall of aurally-presented verbal information is poorer than recall of visually-presented verbal information – quite robust. It appears in multiple reports, and as Logie points out, is observed in other

individuals whose cases are not described in much detail in the published literature. We never suggested that these data were likely unreplicable, nor that they could be explained by assuming that these patients experienced "a general deficit in their focus of attention. . ." (p. 164). However, the consistent evidence of deficient recall of aurally- but not visually-presented verbal sequences should not be conflated with *interpretations* of what that means. The presence of this pattern does not *demand* that one assumes damage to a phonological store. The pattern affords multiple interpretations, whose merits must be weighed. In his comment, Logie hardly acknowledges the sensory-motor integration view (e.g., Buchsbaum et al., 2011; Buchsbaum & D'Esposito, 2008; Buchsbaum & D'Esposito, 2019; Caplan et al., 2012). The sensory-motor integration view of these cases offers an alternative explanation for why recall of aural information specifically might be disrupted. This alternative differs from the multiple-component account in that it does not require positing a phonological short-term store. It does not dispute that a distinctive pattern of results was observed, but shifts the potential source of the problem to communication between aural and motor systems. This should not be derided as "using different labels to refer to what are essentially the same concepts" (p. 162): such a shift in theory leads to different predictions regarding other, related phenomena, even if it does not mean that advice to patients about coping should change at present. Shifting the source of the deficit to communication between perceptual and motor systems highlights a perennial weakness of the multiple component framework, namely that the way in which the components interact with each other and with related systems remains under-specified. This is a key area in which the multiple component account needs refinement, and might be improved by serious consideration of the sensory-motor integration account.

Going forward, collaboration between proponents of different theoretical positions (such as the one two of us, NC and SR, are currently engaged in with Logie) might prove

helpful. It provides a clear forum to compare ideas and ensures that competing interpretations cannot be ignored. For example, Rhodes et al. (2019) tested for and found an indication of competition between storage and processing in the form of a trade-off between two tasks with shifting emphasis (consistent with some degree of domain generality). As Logie notes, the data from this and a related study (Doherty et al., 2019) did not fully match anyone's predictions. In effect, these data falsified particular versions of each model, bringing future iterations closer. Given the important practical implications of understanding the nature of these neuropsychological cases, future research investigating the neuropsychology of working memory would benefit from similar collaborative approaches.

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