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Review

Receptive versus interactive video screens: A role for the brain's default mode network in learning from media

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ABSTRACT

Recent neuroscience research has revealed the presence of multiple brain networks underlying functional human psychology. One of these, the default mode network (DMN), has been shown to underlie sustained attention to and comprehension of narrative receptive media such as television. We argue that DMN activation enhances learning of temporal and spatial context and that this type of learning is characteristic of receptive media. We hypothesize that response demands during interactive screen media use deactivates the DMN as other brain networks are activated. We suggest that overt responding to interactive demands requires highly focused attention and enhances stimulus-response-goal associative learning at the expense of learning about temporal and spatial context. Receptive and interactive screen media, therefore, enhance different types of comprehension and learning.

A trend in educational media programming for adults and children has been to use multiple media platforms presenting both interactive and non-interactive content. Evaluation research of such "transmedia" or "cross platform" programming has indicated that the multiple media approach may be more educationally effective than use of a single medium (Fisch, Damashak & Aladé, 2016; Raybourn, 2014). A question arises as to whether there is a principled reason to use an interactive or non-interactive screen medium with respect to particular educational goals. Here, we will argue that there is reason to believe that interactive screen media enhance different types of learning than receptive (non-interactive) media. The argument is based on the hypothesis that each medium tends to activate different functional brain networks.

In 2006, in a special issue of the journal *Media Psychology*, a diverse group of researchers argued that then-new noninvasive neuroimaging could be usefully applied to studying screen media (Anderson, Bryant, et al., 2006). One of the papers in that special issue concerned the identification of cortical regions that were uniquely activated while adults watched coherent filmic montage taken from Hollywood movies as compared to activation while watching random (as well as highly fragmented) sequences of the same shots (Anderson, Fite, Petrovich, & Hirsch, 2006). That paper argued that the pattern of activation was highly suggestive of a coherent cortical network utilized for comprehension of filmic montage. Two cortical regions were central to that hypothesized network: posterior cingulate cortex, and inferior parietal lobule (see Fig. 1). These regions have been identified as part of a neural network known as the default mode network (DMN; Buckner, Andrews-Hanna, & Schacter, 2008; Raichle et al., 2001).

In this paper we review research that has identified the DMN as central to the comprehension of narrative conveyed by receptive media, including video, audio, and audiovisual. By *receptive media* we refer to media such as television that ordinarily require no overt responses other than attentional orientations in order to receive, perceive, and comprehend the content. We prefer the term receptive media to the commonly used term "passive" media insofar as passive implies that the media user is not cognitively active. We contrast receptive media to *interactive media* (such as computer games) that typically require some form of overt responses in order for the content to unfold over time. When experiencing receptive media, as long as the user is attentive, the content unfolds in a predetermined manner. With most interactive media, what the user experiences depends in part on the user's overt responses.

We hypothesize that coherent receptive media activate the DMN with consequent enhancing effects on comprehension and memory of specific aspects of the program content. In contrast, we hypothesize that interactive screen content likely deactivates the DMN and instead activates other brain networks, enhancing comprehension and memory for different specific aspects of program content. If this argument is correct, the choice to incorporate interactivity into audiovisual screen content has implications for what kind of learning is most likely to occur. This decision has major implications for the design and choice of

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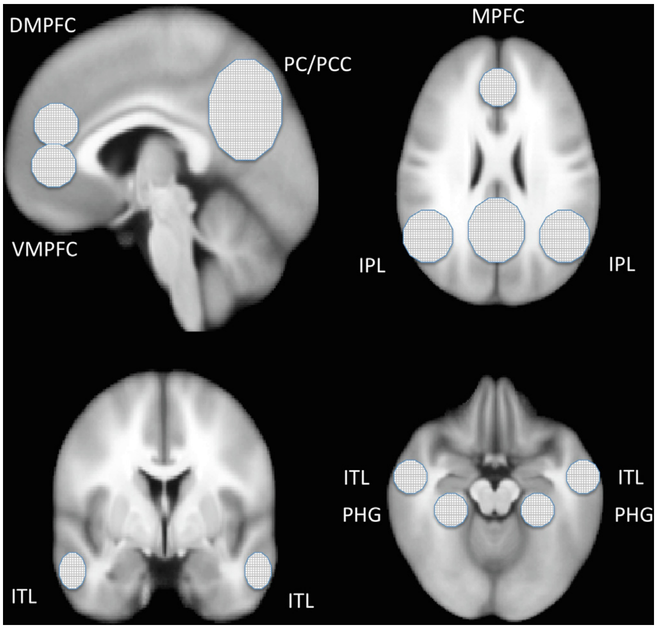

Fig. 1. Depiction of the main regions identified in the default mode network in the human brain, based on Buckner et al., 2008 and Taylor et al., 2012. DMPFC = Dorsal Medial Prefrontal Cortex; VMPFC = Ventral Medial Prefrontal Cortex; PC/PCC = Precuneus Cortex/Posterior Cingulate Cortex; IPL = Inferior Parietal Lobe; PHG = Parahippocampal Gyrus; ITC = Inferior Temporal Cortex.*.

educational media for children (and adults).

1. Brain networks

In this century psychologically-relevant neuroscience has steadily moved from a focus on the function of particular regions of interest (ROIs) to the role of distributed brain *networks*. Petersen and Sporns (2015) use terms from graph theory and network science to define a network as "… a set of pairwise relationships between the elements of a system – formally represented as a set of edges that link a set of nodes" (p.207). Although networks can be defined at various levels (molecular, cellular, etc.), we focus here on cognitive architectures, emphasizing the relationships between different brain regions relevant to a particular task or situation. These relationships can be defined both in functional and anatomical terms. Functionally, a network may consist of regions that are activated simultaneously (or in close temporal sequence) in a particular situation as revealed by functional imaging, including functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). Anatomically, a network consists of brain regions that are more or less densely interconnected by myelinated pathways as revealed by techniques such as diffuse tensor and diffusion spectral imaging (Petersen & Sporns, 2015).

Brain networks typically have one or more "hub" regions that play a central role in recruiting and activating other parts of the network (or elements of other networks). These hub regions are considered to be central to the operation of the network and are thus central to identifying which network is activated at specific points in time. Consistent with this role, hub regions are typically located near the midline of the brain, allowing relatively short connection distances to other nodes in the network. A hub region is often chosen as a "seed" for investigating network activity. If another region's activity is highly correlated with the activity of the seed, that other region is a candidate for inclusion as an essential part of the network. If the activity of another region is negatively correlated with the activity of the seed, it is considered likely part of a separate network that is inhibited or deactivated by the seed region's network (Petersen & Sporns, 2015). A common term used in the neuroscience literature to describe this situation is *anticorrelation* of networks. The posterior cingulate cortex and the inferior parietal lobule are considered main hubs of the DMN (see Fig. 1). Thus, the areas identified by Anderson, Fite, et al. (2006) as central to the comprehension of video montage indicated activation of the DMN.

Networks that are defined functionally because they have positively correlated activity usually have rich anatomical connections including clustering of network regions, short path lengths, and densely connected network nodes. In general, it is thought that networks serve to reduce neural conduction delays and average length of node-to-node connections. They can also be characterized mathematically as "small world" networks (e.g., Bassett & Bullmore, 2006; Watts & Strogatz, 1998). That said, networks sometimes include indirect and long-distance pathways, and particular network nodes may participate in multiple other networks organized through the activity of differing hubs (Avena-Koenigsberger, Misic, & Sporns, 2018). The brain network of greatest interest in the present paper is the DMN. Other networks of interest will be mentioned relative to particular contexts within this review.

2. Default mode network

In a seminal paper, Raichle et al. (2001) noted that, during imaging of brain activity (using a variety of methodologies), as a person was at rest between trials of an assigned cognitive task, total brain activity was usually not reduced. Because there was little reduction of overall oxygen consumption, rest was as energy-intensive as demanding cognitive tasks. This was surprising, because it had been assumed that there would be less neural activity during rest as compared to a mentally demanding task, but instead there was consistent activation in particular brain regions. When an assigned cognitive task was resumed, this resting network was deactivated as other brain regions became active. Raichle labeled the regions that are active during rest the Default Mode Network (also known as the Default Network). When adult research subjects were asked what was going on during rest periods, when the DMN was most likely to be active, the most frequent response was some version of "mind wandering". Subsequent functional and anatomical network analysis revealed the DMN as the most directly and densely connected neural network compared to all other known networks suggesting that it is fundamental to waking brain function (Horn, Ostwald, Reisert, & Blankenburg, 2014).

In a review, Buckner et al. (2008) identified three brain regions as DMN hubs: posterior cingulate cortex (and adjacent retrosplenial cortex), inferior parietal lobule, and medial prefrontal cortex. Other regions may be activated depending on the particular situation, especially the medial temporal lobe including the hippocampal formation which are often included as part of the DMN. The involvement of the medial temporal lobe is suggestive that the DMN is important for episodic memory and, as we discuss later, for spatial cognition. Buckner et al. (2008) noted that the DMN is activated not only during mind-wandering in rest periods, but also during assigned tasks such as future planning involving the self, autobiographical memory, and interpreting social interactions. During overt cognitive task situations requiring highly focused attention, on the other hand, the DMN is deactivated but tends to become active when people make errors. In effect, mind wandering during a demanding focal attention task causes distracted errors. Rather than viewing the DMN as some sort of non-cognitive daydreaming network, Buckner et al. (2008) argued that the DMN is activated in situations that require broad situational awareness over time and is deactivated during task situations requiring focused attention. In the latter situations, other brain networks, especially the dorsal attention network (DAN), are activated.

Buckner et al. (2008) argued that the subsystems of the DMN play particular broad roles in cognition during DMN activation. The medial temporal cortex node accesses memories relevant to situational interpretation either mentally (as in autobiographical recall), or observationally (as in interpreting observed social interactions). The medial prefrontal region is involved in constructing sequential interpretations of observations of the outside world or in mental simulations such as imagining the future or planning the day's activities. The posterior cingulate cortex is broadly integrative, providing an overall situational interpretation or temporally integrated understanding of a sequence of observed, recalled, or imagined events.

The posterior cingulate cortex (along with adjacent retrosplenial cortex), hereafter referred to as PCC, constitutes a main hub of the DMN, with other hubs being the ventral medial prefrontal cortex, the inferior parietal lobule, and medial temporal lobe. The PCC falls within the posterior midline cortex, the ventral medial prefrontal cortex falls within the anterior midline cortex, and the inferior parietal lobule, especially the region known as the angular gyrus, is lateral to the PCC. Most functional connectivity research focusing on the DMN uses the PCC as the "seed" region for the purpose of calculating pairwise correlations between activity of the hub and of other regions of the brain. It is thought that the PCC plays a substantial role in recruiting other brain areas according to the demands of the particular observational or task situation (e.g., Lin et al., 2016). The DMN, therefore, is not a simple network with an unvarying set of components; rather, it comprises midline hub regions (principally the PCC) that can recruit a variety of subsystems depending on the context in which neural activity is measured. The principal regions of the DMN are illustrated in Fig. 1.

3. Development of the default mode network

The DMN undergoes enormous development, from components that do not function as a network in infancy to the beginnings of network functioning by about age two years (Fransson et al., 2007; Gao et al., 2009). After its initial appearance, the development of the network is protracted. Fair et al. (2008) found that the functional DMN connections in school-aged children, although present, were much weaker than those in adults. Similar findings were reported by Supekar et al. (2010). Fair et al. (2009) found that childhood networks tend to be anatomically clustered among nearby structures but with maturation, long distance connections develop into the adult networks. Chai, Ofen, Gabrieli, and Whitfield-Gabrieli (2014) reported that the anticorrelation of the DMN with other networks increased from 7 to 24 years of age. In sum, there is substantial development from weak local connections to stronger and more distal functional connections of the DMN from middle childhood to adulthood. This is suggestive that psychological functions that depend on DMN, such as comprehension of receptive screen media, themselves undergo protracted development.

4. The DMN and receptive media

The DMN is strongly implicated in the processing, comprehension and memory of narrative receptive media including aural, audiovisual, and text media. Raichle (2000) may have been the first to note that the DMN appeared to become activated during television viewing. In order to reduce boredom by research subjects during scanning sessions, and in order to keep them from falling asleep, his research group began showing video clips during rest intervals. Approximately the same structures were activated (i.e., DMN) as compared to when the subjects were shown a static image of crosshairs. In other words, when watching a structured TV program, similar brain structures were activated as compared to when subjects engaged in unstructured "mind wandering".

As noted above, Anderson, Fite, et al. (2006) found that DMN hub structures were uniquely activated when adult subjects were shown 40s segments of Hollywood movies in the original form (without audio), but not when the shots were shown in random order, or as brief randomly sequenced fragments. Based on the literature available at the time, the authors argued that "… posterior cingulate activation may underlie the ability to achieve a global evaluation of the significance, meaning, and memorability of a visual action sequence" (Anderson et al., 2006, p. 20). Since then, a coherent literature has grown supporting this interpretation as well as the role of the PCC and the DMN in comprehension of audiovisual screen media.

When adult viewers watch a Hollywood movie or sitcom, across individuals, roughly the same areas of the brain are activated at the same time (Hasson, Nir, Levy, Fuhrmann & Malach, 2004). That said, some parts of the media program produce higher momentary correlations in activation across subjects than do other parts of the program. These highly correlated portions of the programs are substantially more likely to be remembered 3 weeks later than portions that produce activations that are less correlated across viewers (Hasson, Furman, Clark, Dudai, & Davachi, 2008). The brain areas of correlated activation that are most reliably implicated in comprehension and memory of receptive media constitute portions of the DMN (Hasson, Malach, & Heeger, 2010). Imaging studies that include tests of memory and comprehension thus show that DMN activation during receptive media use is strongly related to comprehension.

Temporal aspects of narrative comprehension play a central role in DMN narrative processing. Hasson, Yang, Vallines, Heeger, and Rubin (2008) postulated a "hierarchy of temporal receptive windows" in the brain that integrates narrative information at various levels of elapsed time into content units of a narrative. They used a version of the Anderson, Fite, et al. (2006) experimental paradigm, showing silent movies to adult subjects. One version was normal, one had randomly edited sequences according to 3 temporal scales (approximately 4, 12, or 36 s), and a third ran backward. As found by Anderson and colleagues, Hasson, Furman, et al. (2008) and Hasson, Yang, et al. (2008) reported DMN activation, but only for the normal version. In analyzing the temporal patterns of activation to the normal version in comparison to the other conditions, they argued that some areas (such as primary visual areas) integrate information over relatively brief periods of time, whereas other areas integrate information over intermediate periods of time (approximately 12s), and yet others over much longer periods of time (a half-minute or more). The structures integrating information over longer periods of time are within the DMN. In contrast, these DMN structures were not consistently activated in the backward film version or in the shorter random segment condition. In subsequent work building on this conception, Baldassano et al. (2017) argued that there is "… a nested hierarchy from short events in sensory regions to long events in high-order areas (including angular gyrus and posterior medial cortex), which represent abstract, multimodal situation models … High-order event boundaries are coupled to increases in hippocampal activity, which predict pattern reinstatement in free recall" (p. 709). They found intense brief hippocampal activation during movie viewing at event termination boundaries as marked by independent observers. Furthermore, they found reinstatement, during free recall, of the unique patterns of neural activation observed during encoding. These findings indicate a strong role of the DMN in encoding, comprehension, and memory for the temporal connections in a coherent narrative.

Nakano and collaborators have argued that DMN is activated for only brief periods of time during TV viewing. They found that viewers tend to blink at content boundaries compared to other portions of narrative content (Nakano, Yamamoto, Kitajo, Takahashi & Kitazawa, 2009). Content boundaries, in this context, are implicit breakpoints that occur when one unit of action or dialogue ends and another begins (Newtson, 1973). Blink synchronization, across adult viewers, did not occur if the video content was not structured as a narrative (for example a series of unconnected video shots of nature scenes) consistent with other studies of DMN activation during narrative processing. In related work, the researchers suggested that blinks serve to release external attention (presumably directed at the TV program), deactivating the dorsal attention network (DAN) and briefly activating the DMN therefore allowing temporal information integration (Nakano, Kato, Morito, Itoi, & Kitazawa, 2013). Nakano (2015; 2017) found experimental evidence that spontaneous blinks are associated with activity in the angular gyrus, a portion of the inferior parietal lobule and replicated the finding of DMN intensification accompanied by blinks at content breakpoints. He noted activation of the hippocampal formation along with other DMN structures, strongly suggestive of the importance of blink-related DMN activation to episodic memory of TV program content.

Baldassano et al. (2017) also found intense activation of angular gyrus and hippocampal gyrus at narrative breakpoints but argued that within the sustained activation of DMN during narrative processing there is also a memory dynamic driven by narrative structure. It is likely, therefore, that DMN activation dynamically changes within its components and that these changes serve to enhance comprehension and memory in relation to structural characteristics of the narrative being processed. Taken together, these studies reveal some differences between research groups in the temporal dynamics of DMN activation but they are in agreement on the importance of the DMN for the temporal integration essential to connected comprehension of narrative content.

The role of the DMN in narrative comprehension is not limited to screen media. Lerner, Honey, Silbert, and Hasson (2011), using fMRI, scanned adults as they listened to auditory stories. The stories were intact, scrambled at the level of paragraphs, or scrambled at the level of sentences. As was found for silent movies (Hasson et al., 2008), there appeared to be a hierarchy of temporal receptive fields with low level auditory and language processing areas accumulating information over relatively brief windows of time, whereas other areas were activated only by the intact paragraphs or entire stories. These latter areas overlapped considerably with areas of DMN that had been activated in the Hasson et al., 2008 study by intact silent movies. More recently, Tikka, Kauttenen, and Hlushchuk (2018) found that the same networks (principally the DMN) are activated by the same parts of a narrative whether read as text or viewed as a movie. The DMN thus appears to have an abstract narrative function, integrating causal and contextual information across entire stories. Given these findings, it is not surprising that adults who listened to the same stories in different languages activated these same narrative comprehension structures (Honey, Thompson, Lerner, & Hasson, 2012). Along this line, many of the same DMN-related structures were activated regardless of whether adults listened to or read stories (Regev, Honey, Simony, & Hasson, 2013), suggesting that the perceptual or linguistic details of input matter less than the fact that the input is conveying a coherent narrative. Narrative comprehension is supported by the DMN regardless of whether the medium is audio, audiovisual, or text.

It should be noted that the DMN is sensitive to context. Ames, Honey, Chow, Todorov, and Hasson (2015) presented audio passages either with or without a “back story” that clarified the context of the passage (e.g., doing laundry). Only with the back story did the passage “make sense” and consequently activate the DMN. Comprehensibility ratings by the subjects were strongly related to DMN activation. With respect to context, a recent experiment presented two groups of adult listeners a 12-min short story. The groups differed, however, in terms of the particular back story given, providing different interpretations of the characters’ motivations and intentions. Consistent with prior research, the DMN and networks associated with processing language were activated. Nevertheless, there were specific differences in patterns of network activation between the two experimental groups. When processing narrative, therefore, the DMN processes implicit context (Yeshurun et al., 2017).

Taken together the findings indicate that as narratives and input characteristics differ, there are corresponding differences in the specifics of network activation. Silent movie stories activate many brain structures that are responsive to visual stimulation, and aural stories activate many structures that are responsive to auditory stimulation and language. The larger point here is that portions of the DMN are activated by a variety of situations that involve connecting events as they occur over time in specified contexts. Temporal connectives in narrative (and real-life) contexts include simple event sequences, enabling events, character goals, motivational factors, plans, passage of time, cause and effect, and many others. Understanding temporal connectives is essential to understanding stories, many expositions, and real life (e.g., Schank & Abelson, 1977). In summary, the DMN appears to play a central role in comprehending events that are temporally connected.

5. Screen versus screen: DMN deactivation during interactive media use

Recall that when the DMN is activated, other neural networks in the cognitive architecture are usually deactivated and vice versa (Buckner et al., 2008; Zhou et al., 2018). For example, in tasks that require focused attention, combined with fast and accurate responding, the DMN is deactivated while the DAN is activated (e.g., Lin et al., 2016). We argue that there is therefore a major implication for interactive screen media as compared to receptive media. *We hypothesize that during interactive media use, the DMN is usually deactivated. A consequence is that interactive and receptive media foster different kinds of comprehension and learning.* A corollary of this hypothesis is that the more that screen media content is structured as a narrative, without demanding focused attention and fast responses, the more the DMN will be activated. Interactive screen media typically require the activation of fronto-parietal networks, such as the DAN which underlies focused attention, and task-positive networks (including executive function and motor response preparation regions). When these networks are activated, the DMN is usually deactivated (e.g., Kwon, Watanabe, Fischer, & Bartels, 2017). An exception to this rule is implied by an argument from Smith, Mitchell, and Duncan (2018) to the effect that in demanding task situations with multiple task components that require self-monitoring in order to appropriately switch tasks, the DMN may become briefly activated once the task is well-learned. They suggest (p. 3685) that “… DMN encodes scene, episode, or context, by integrating spatial, self-referential, and temporal information.” That is, in tasks that require the participant to monitor transitions (behavioral, spatial, temporal) the DMN may be briefly invoked to create an overall contextual comprehension of the task as well as to plan future actions necessary to task completion.

We hypothesize that when the DMN is active, the media user is more likely to make both short- and long-term inferences about the causal and temporal relationships between events and that these are related to context, including spatial context. Consequently, receptive media are more likely to allow the user to create an overarching representation of the causes, consequences, and context of the screen presentation. Interactive media, on the other hand, are more likely to allow the user to make local associative connections with stronger memories of specific events and concretely associated objects and settings. Learning from interactive media will thus be more tightly focused in space and time than learning from receptive media.

We hypothesize other differences between receptive and interactive media. When the DMN is active, during receptive media use, the experience is less fatiguing. This follows from observations and self-rating by viewers that most television viewing is not cognitively demanding relative to tasks requiring focused attention and accurate responses (e.g., Salomon, 1983). In fact, part of the discovery of the DMN's role in television viewing was because video clips were used as a form of rest between demanding cognitive tasks (Raichle, 2000). Use of interactive media, therefore, should be more difficult to sustain without fatigue than use of receptive media.

A major qualification in our argument should be noted here. Receptive screen media such as broadcast television have essentially three types of content: narrative, expository, and hortatory (as in commercials). User responses are largely limited to being more or less attentive. Interactive media, in contrast, vary much more widely and are more difficult to characterize in simple terms. They can be principally social in nature (e.g., text-based social media, messaging apps, audiovisual live communication, e.g., Skype), textual and expository (e.g., any text-based form with hyperlinks such as Wikipedia), textual and narrative (e.g., fan fiction internet sites), and audiovisual following a large variety of content forms. For example, audiovisual interactive games can vary widely in form and content, ranging from character-based narrative forms (e.g., various kinds of adventure games), to object manipulation (e.g., puzzles, card games), to dancing and exercise games. It is thus easier to generalize with respect to receptive media than it is to generalize about interactive media.

Surprisingly, we have not found a research literature on brain network activation for interactive media that parallels the research literature for receptive media. Research on gaming that has examined network activation has largely focused on specific types of content, especially violent gaming content compared to nonviolent gaming content (e.g., Zyagvintsev et al., 2016). This literature is not helpful in testing our hypotheses. There has been some brain network research on "presence" or the sense of "being there" during interactive game play, as well as the sense of "flow" during gaming (for a review see Klasen, Weber, Kircher, Mathiak, & Mathiak, 2012). Broadly speaking, these studies implicate the fronto-parietal networks in game play, including the DAN, consistent with our hypotheses. None of these studies, however, specifically examine DMN deactivation during game play.

Adults are able to control DMN activation insofar as they suppress mind-wandering when tasks demand focus focused attention and active responding (Sormaza et al., 2018). This presumably happens during interactive computer use as well. Dixon et al. (2017), however, argued that DMN and DAN are not necessarily anticorrelated, insofar as the relationship varies with task demands. In other words, in healthy adults, the DMN and DAN may sometimes have positive functional connections in particular task situations (such as complex tasks with sequential components, as noted earlier). Until there is more relevant research on brain networks, we assume that DMN deactivation is typical during interactive media use.

Spatial processing. Recent animal research has found that activity in the basal forebrain, including structures in the basal ganglia plays an important role in activation and deactivation of the DMN (Nair et al., 2018). This has direct relevance to a theory of spatial learning from computer games. West, Konishi, and Bohbot (2017) argue that the striatum, (caudate nucleus and putamen of the basal ganglia), plays an important role in stimulus-response-goal (S-R-G) learning especially in many computer games. It is also part of the spatial memory system associated with egocentric space, that is, the layout of space relative to one's own body. When this system is activated, the hippocampal complex, part of the DMN, becomes deactivated, and presumably accompanied by DMN deactivation more generally. The hippocampus, in contrast to the striatum, is part of the spatial memory system that maps allocentric space, or the objective relationships of locations in space relative to each other and independent of the positions of one's own body (for references, see West et al., 2017). For example, you likely know that New York City is northeast of Atlanta regardless of where you are with respect to either of them, or more narrowly, where the windows in your bedroom are relative to the bed (an excellent discussion of the perception of egocentric versus allocentric space can be found in Milner & Goodale, 1995).

In reviewing gaming research, West et al. (2017) argue that frequent speeded responses narrow the focus of attention to stereotyped S-R-G sequences that eventually become overlearned. This leads to activation of the caudate nucleus of the striatum, which underlies S-R-G learning. The narrowed focus of attention and striatal activation is associated with reduced hippocampal activation. Thus some types of games that require rapid speeded responses (e.g., shooting multiple pop-up enemies) activate the striatum and create egocentric spatial representations of the game environment. In contrast, they hypothesize that games that do not require frequent rapid responses activate the hippocampus (and possibly the larger DMN especially if the exploration is part of a larger narrative). This allows the creation of allocentric spatial representations of the game environment, consistent with the situational awareness characteristic of DMN activation. In other words, when the hippocampal complex is activated, a more comprehensive, abstract, and general representation of the game environment is created. The West et al. (2017) hypothesis about gaming and spatial cognition is thus consistent with ours, especially insofar as the hippocampal complex is part of the DMN. Consistent with this hypothesis, Havranek, Langer, Cheetham, and Jäncke (2012) reported activation of cortical regions during game play consistent with egocentric spatial processing. They did not find activation of these regions during receptive processing of the same content.

In a behavioral study, Knight and Tlauka (2017) compared "active" map learners (interactive scrolling across a map) with receptive map learners (watched as the map was scrolled). Cognitive load was varied by means of a simultaneous tapping task. Under high cognitive load conditions (more difficult tapping task), adults showed better map learning in the receptive condition. There were no differences in map learning when the cognitive load was low. Again, when a difference was found, the receptive condition was more beneficial for learning an allocentric spatial layout, consistent with the West et al. (2017) analysis.

It should be noted that a substantial number of studies have examined "active" versus "passive" learning of spatial layouts, with mixed results (for references see Knight & Tlauka, 2017). Some studies find an advantage for active exploration of the environment and others find an advantage under receptive or "passive" conditions. These studies vary considerably in what is meant by "active" as compared to "passive" learning (e.g., driving through an environment versus being driven through the same environment) and in the types of learning tested (e.g., navigation versus knowledge of relative locations of objects). It should also be noted that many of these studies did not use screen media for learning conditions. For now, we assume that allocentric spatial learning is a concomitant of DMN activation.

6. Evidence from studies of receptive screen media

In addition to the brain network research reviewed above, there is a substantial amount of behavioral research that is consistent with the role of the DMN in processing receptive media. According to surveys of parents, children begin to use receptive and interactive screens before a year of age, including touch screens if they are given access (e.g., Rideout, 2017).

If DMN activation underlies sustained attention to and comprehension of receptive audiovisual media, then we would expect that these would develop in parallel with the maturation of the DMN. The behavioral literature is consistent with this expectation. Visual attention to television observed both at home and in the laboratory steadily increases with age from infancy through the preschool years (e.g., Anderson & Levin, 1976; Anderson, Lorch, Collins, Field, & Nathan, 1986). Episodes of visual orientations toward the TV screen, referred to as "looks", increase both in frequency and duration. Insofar as development of the DMN involves the development of receptive temporal windows (Hasson et al., 2008), it is reasonable to expect that sustained looking at TV would increase during this time period.

Detailed analyses of the distribution of look lengths at television have indicated that they are lognormally distributed, that is, while most spontaneous looks at television in naturalistic contexts are relatively brief, lasting for a few seconds, some may be as long as 10 min or more in duration (for a review, see Richards & Anderson, 2004). This is consistent with Hasson's et al. (2008) notion of temporal windows, some of which (closely tied to basic perception) are quite brief, yet others of longer (on the order of 10 s) duration, tied to the comprehension of local action sequences, and still others of much longer duration (minutes) tied to comprehension of the narrative as a whole. Behavioral research has indicated that as looks at television continue in time, the viewer becomes progressively less likely to terminate attention, becomes less distractible away from the screen, increases recognition memory of the content, and is more likely to make bridging inferences that connect different portions of the narrative. Collectively, this phenomenon, tied to the lognormal distribution of look lengths, has been called *attentional inertia* in television viewing (Anderson, Alwitt, Lorch, & Levin, 1979; see Richards & Anderson, 2004 for a literature review). It is completely consistent with progressive activation of higher-level temporal receptive windows identified as part of the DMN.

If, as hypothesized here, the DMN is the network that provides connected comprehension of narrative content, it would be expected that the increase in narrative comprehension seen throughout development is greatly related to increased comprehension of the temporal relationships implicit in the narrative content. This is just what has been found in studies of story comprehension including television (e.g., van den Broek, Lorch, & Thurlow, 1996).

If activation of higher-level temporal receptive windows of the DMN underlies sustained attention to receptive media, then disorders related to deficits in sustained attention and comprehension may be reflected in processing of receptive media. Many studies have reported weaker connections within DMN and between DMN and attention control nodes in children diagnosed with ADHD (attention deficit with hyperactivity disorder) that continues into adulthood if ADHD symptoms remain (e.g., Sudre, Szekely, Sharp, Kasparek, & Shaw, 2017). This suggests that ADHD influences sustained attention as well as comprehension of receptive media. In fact, children diagnosed with ADHD have fewer sustained looks at television than non-diagnosed children when they are shown programs in an environment where there are alternatives to looking at TV such as toys to play with (e.g., Landau, Lorch, & Milich, 1992). Correspondingly, narrative comprehension of television is reduced, particularly temporal inferences necessary to connect different portions of the narrative. These inferences are most likely to be made when looks at TV have been sustained for 15 s or longer (for a review see Lorch, Berthiaume, Milich, & van den Broek, 2007).

Consistent with its role in comprehension, neuroscience investigations reveal that the DMN is activated by coherent edited narrative video but not when the same video is presented in noncanonical or randomized order. These observations correspond with behavioral studies of visual attention to television in relation to comprehension. Looking at television is less sustained when viewers watch video segments that have shots in random order or if the dialogue is backward or in a foreign language (e.g., Anderson, Lorch, Field, & Sanders, 1981). Developmentally, randomizing shot sequences or using backward dialogue disrupts visual attention to video only beginning at 18 months of age and robustly disrupts attention by 24 months of age (Pempek et al., 2010). Given that the DMN does not begin to show network connectivity until about 24 months (Gao et al., 2009), these findings are again consistent with the idea that the DMN underlies sequential comprehension and thus sustained visual attention to video. In this view noncanonical shot sequences prevent activation of long temporal receptive windows (and associated neural structures such as posterior cingulate) and thus sustained attention. This only begins to happen once the DMN has sufficiently developed to support comprehension of edited video.

The intersubject correlations of brain electrical activity are substantially greater during coherent audio and audiovisual narrative (Ki, Kelly, & Parra, 2016) than during the same material presented in a scrambled manner. Similarly, coherent narratives are associated with greater consistency in visual fixation points between video screen viewers – that is, viewers are more likely to look at the same place on the screen at the same time (Kirkorian & Anderson, 2018; Wang, Freeman, Merriam, Hasson, & Heeger, 2012). If the DMN underlies narrative processing in general, we would expect that parallel developmental trends in comprehending narrative would be found across media. In fact, patterns of comprehension by children for aural stories are fairly closely related to patterns of comprehension of the same stories in audiovisual form (e.g., Gibbons, Anderson, Smith, Field, & Fischer, 1986; Neuman, 1992), or digital aural (ebook with a “read to me” feature) versus a caretaker reading aloud (Neuman, Wong, & Kaefer, 2017). Theories of text comprehension work well in predicting comprehension of audiovisual content (Anderegg, Alade, Ewoldsen & Wang, 2017; van den Broek et al., 1996), consistent with the theory that the same brain mechanisms underlie abstract narrative comprehension across media. These parallels provide further support that narrative comprehension is organized by the DMN and that such comprehension is not tied to audiovisual screen media only.

In preschool children Cantlon and Li (2013) reported that *Sesame Street* segments that focused on number concepts activated portions of the DMN known to be related to numerical cognition (a region of the inferior parietal lobule, inferior parietal sulcus). This activation was found to be related to learning from the segments as well as to standardized achievement tests. The degree to which the activation correlated with adult activation (while watching the same segments) predicted the degree of learning and achievement by the children. That is, the more mature was the pattern of activation, the greater the achievement. Thus, specific DMN activation during viewing appears directly related to what children learn from television.

Before discussing interactive screen media, it is important to note that behavioral passivity is not required for DMN activation. A study of free toy play in preschool children has found DMN activation as the children physically manipulate the toys (Kim et al., 2017). Child free play could thus be viewed as a form of embodied mind-wandering. It is well known that a great deal of free toy play consists of story-like play schemes that the child overtly and verbally acts out (e.g., Bretherton, 1984). Consistent with this observation and consistent with the notion that creation of extended play “stories” involves activation of long-lasting temporal receptive windows, toy play episodes are lognormally distributed in length, as are looks at television, with similar growth in resistance to external distraction as the play episode continues (Anderson, Choi, & Lorch, 1987; Choi & Anderson, 1991). The main point here is that physical inactivity is not a prerequisite for DMN activation.

Evidence from Studies of Interactive Screen Media. We have hypothesized that, in comparison to receptive screen media, the demands of interactive screen media are likely to deactivate the DMN as other networks are activated. We have not been able to find any brain network research that directly tests this hypothesis.

Much of the neuroscience literature on interactive media is focused on the long-term effects of gaming on brain activation, often comparing dedicated (or “addicted”) gamers to relatively inexperienced gamers (e.g., Gong et al., 2016). There are reports within this literature of differences in functional and structural connectivity of the DMN and fronto-parietal networks when heavy gamers are compared to individuals who do not frequently play computer games (e.g., Bae, Han, Jung, Nam, & Renshaw, 2017). While this finding is loosely consistent with our hypothesis of deactivation of DMN during game play (and consistent with activation of fronto-parietal networks) it does not address the central concern of this paper: specifically, that deactivation of the DMN during interactive media use enhances some forms of comprehension and learning at the expense of others.

Other lines of screen media research evaluate brain activation relative to games designed as interventions for particular medical or psychological conditions (for a review see Shams et al., 2015). While such research is of considerable interest in its own right, it does not provide comparisons of brain network involvement in interactive as compared to receptive media.

We have found a few neuroscience studies that partially support our hypothesis. Oren et al. (2016) presented 21s excerpts from Hollywood movies while adults were being scanned via fMRI and presented a secondary task simultaneously with the movie excerpt. This task required the viewer to judge whether a visually presented word (below the movie) was a real word or a pseudo-word. The secondary task had the effect of reducing activation of PCC (a main hub of the DMN). This reduction was associated with reduced recognition memory for scenes from movies. While the secondary task is clearly not interactivity in the usual sense, it is suggestive that to the degree to which interactivity distracts from processing the video, memory for video content will be reduced. Weber, Alicea, Huskey, and Mathiak (2018) report increased functional connectivity of attentional networks (particularly the DAN) as play of a first-person shooter game continued without distraction. Insofar as DAN connectivity is typically anticorrelated with DMN connectivity, the study provides direct evidence of DAN involvement in computer game play and indirect evidence of DMN deactivation. Havranek, Langer, Cheetam, and Jäncke (2012) compared interactive game play to simply receptively watching a recording of another person's play of the same game. Using EEG with source localization analyses, they found activation of fronto-parietal regions (including DAN). They did not report which regions showed greater activation during receptive viewing of game play, so again these findings provide only indirect support of our hypothesis. Similarly, Sampaio Barros, Arájuo-Moreira, Trevelin, and Radel (2018) found fronto-parietal activation while playing *Tetris* or *Pong* and hypothesized deactivation of the DMN but without directly demonstrating it.

Comparisons of Interactive and Receptive Media. We have not been able to find any direct comparisons of brain network activation during use of interactive and receptive screen media other than the studies cited above. One unique study provides a meta-analysis of fMRI studies that used "naturalistic" media, that is, dynamic visual, audio, audiovisual, or tactile media (Bottenhorn et al., 2019). The meta-analysis identified six patterns of brain activation across all the dynamic media studied. Of particular interest here, the presentation of their findings allows broad comparisons of brain activation during use of receptive screen media or video games. The receptive media were films and videos used mostly in studies of violence, emotion, and eroticism. The video games were mostly used in studies of violent gaming. The first broad pattern of brain activation concerned brain structures associated with attention and the processing of dynamic visual features. More activation of these structures was seen with receptive media than video games. The second broad pattern concerned language processing, inference, and perception of congruity, with less activation for receptive media. The third pattern concerned emotion and social processing with no apparent difference between receptive and interactive media. The fourth pattern concerned spatial navigation and spatial memory, with more activation during video games. The fifth pattern concerned music and sound processing, with greater activation in films and video. Finally, the sixth pattern concerned attentional demands associated primarily with the DAN. Activation of this system was greater during video games. This meta-analysis combines data from many studies with widely varying purposes and employing dynamic stimuli of diverse natures. While we would expect activation of the DAN during video games, as was found, we would also expect greater inference and perception of congruity with receptive media which was not found. However, because many of the studies employing receptive media used brief stimuli with no expository or narrative context (e.g., a video clip of a person crying), this diversity may have obscured the findings we would expect. If a video has little temporal or narrative structure, for example, we would expect little activation of the DMN. Similarly, if a video is shot in a single room or limbo (no discernible background context), we would not expect activation of brain regions that process spatial layout.

Experimental comparisons between interactive and receptive media. There have been a few controlled behavioral studies that allow us to determine whether memory and comprehension patterns differ as we predict. In particular, we predict that receptive media enhance learning of temporal connections across narrative (and possibly expository) content, as well as allocentric representation of the space in which the content takes place (assuming there is such a space to represent). In contrast, interactive media enhance learning of specific stimulus-stimulus and stimulus-response-goal associations as well as egocentric representations of space. We predict a superiority of associative learning with interactive media because interactive media likely activate the focused attention networks, and task positive networks associated with high performance and memory for arbitrary relationships. Similarly, interactive media should enhance performance in situations where representations of egocentric space are most appropriate (for example, manual skills such as knot tying), whereas receptive media should enhance performance in situations where allocentric representations of space are most useful (e.g., finding a location in a park when one enters it from a different entrance than previously used). In addition, we predict that interactive media use is more fatiguing than receptive media use insofar as DMN activation is associated with activities such as rest between tasks, daydreaming, and the like. On the other hand, because S-R-G interactive media use activates basal ganglia, leading to dopamine release in anticipation of reward (Knutson & Bossaerts, 2007; Knutson & Cooper, 2005; Li, Liu, D'Argembeau, Ng, Bechara, 2010), the experience of interactive media use may be perceived as more rewarding and therefore engaging (albeit relatively fatiguing).

It should be pointed out that experimental comparisons between media are always problematic. It is rare for media comparisons to have absolutely comparable content. It has been long recognized that when comparing commercial productions, producers of each medium maximize the effective qualities inherent in that medium, making comparisons necessarily confounded in multiple ways (Clark, 1983).

Because the DMN and other brain networks undergo great development, the following review is organized developmentally. It is also the case that most relevant studies have been conducted with young children.

Toddlers. The DMN only begins to show network connectivity when children are about 2 years old (Supekar et al., 2010), although components of the DMN are active before that age (Gao et al., 2009; Xu et al., 2017). Beginning at about 2 years of age, children sustain looking at coherent video relative to random shot sequences (Pempek et al., 2010). This finding is consistent with the DMN becoming influential on sequential comprehension as the network assembles developmentally. If so, we expect differences in learning between receptive and interactive screen media to emerge between two and three years of age and that the differences should be related to the nature of the presentation as well as the kind of interactivity required. In this context it should be noted that toddlers around 2 years of age have difficulty transferring information from representations (whether on screen or on paper) compared to viewing equivalent unmediated ("real life") displays. This "transfer deficit" is partly related to issues of transferring from 2D to 3D test situations (and the reverse), and partly related to the lack of social scaffolding in media presentations as compared to "real-life" unmediated situations (for recent reviews and research see Hipp et al., 2017; Kirkorian, Choi & Pempek, 2017). The focus here is on learning and transfer from receptive and interactive media compared to each other, not with unmediated situations.

Interactive media are more effective than receptive media in promoting 2-year-olds' learning and transfer when the interactions have genuine social reciprocity (as in interacting via a video chat program such as Skype). Note that when children are engaged in social screen interactions, there are not the same kinds of demands for focused attention and accurate responses as compared to most video games. That said, the comparison does not provide a clear test of our hypothesis insofar as activation of the DMN occurs during social interactions with other people (for a review see Li, Mai, & Liu, 2014). Nevertheless, real time social reciprocity allows toddlers to better transfer information conveyed by an interactive screen character than when receptive video of the same character is viewed. The social reciprocity of real time screen interaction is superior for transfer in imitation tasks (Nielsen, Simcock, & Jenkins, 2008), word learning (Roseberry, Hirsh-Pasek & Gollinkoff, 2014) and toy finding (Troseth, Saylor, & Archer, 2006).

Why this is true, at least in terms of the details of DMN activity remains to be determined since the DMN is likely activated in both situations. One possibility is that learning during reciprocal social interactions is especially important during early and late infancy and supported by unique forms of brain activity (e.g., Conboy, Brooks, Meltzoff, & Kuhl, 2015).

Because the DMN emerges as a connected network during the third year of life we expect that differences in receptive versus interactive learning and transfer also emerge during this period. Several lines of evidence indicate that connected comprehension of television emerges between 2 and 3 years of age (for a review see Anderson & Hanson, 2010). Associative learning and haptic exploration develop much earlier. We therefore predict that where there are differences, learning from interactive screens will be better for younger toddlers, with advantages of receptive screens only emerging in the latter half of the third year of life.

An experiment compared word learning by 24- to 36-month-olds from a receptive video program shown on a tablet to the same program presented interactively via touch screen (Kirkorian, Choi, & Pempek, 2016). In the receptive video version, an actress on the tablet screen referred to an object in a box and provided an auditory label for that object. There were two interactive versions: after the object was labeled, one version required the child to touch anywhere on the screen in order to continue the program and see the object. In the other version, the child was required to touch directly and specifically on the box in order to continue the program and see the object. Following the presentation, the child was assessed for learning of the object's label. If the DMN substantially assembles itself as a connected network between age 2–3 years (Supekar et al., 2010), one might expect systematic age changes in learning from the two different forms of screen media during this time.

Age changes were in fact found: Younger 2-year-olds learned best from the interactive specific touch screen condition, whereas older 2-year-olds learned best from the receptive video condition. Our interpretation is that in the younger 2-year-olds, the specific touch screen condition enhances activation of focused attention networks and therefore specific associative learning. In contrast, the receptive screen condition may be unable to activate the immature DMN with the consequence that there is no connected comprehension of the presentation and so attention to the relevant information is somewhat diffuse. In older 2-year-olds, on the other hand, the receptive video condition activates the now-somewhat-functional DMN, producing superior learning as was found. Consistent with our interpretation, Kirkorian et al. (2016) hypothesized that the children were able to learn the word meaning through the entire context of the presentation; the social intention of the “teacher”, the movements of the teacher, and the spoken words. The touch screen presentation, in contrast, may have focused the children's attention on the touched object, leaving little capacity for absorbing the larger temporal and spatial context. This interpretation is consistent with the touch screen activating the dorsal attention network, leading to focused stimulus-response-goal learning, whereas the receptive video activates the now-more-connected default mode network.

This reversal in screen effectiveness during the third year of life is not limited to word learning. Using the same research design as Kirkorian et al. (2016), Choi and Kirkorian (2016) presented a hidden object task. Again, the younger 2-year-olds showed superior learning and transfer from the specific touch screen task compared to receptive video, but the older 2-year-olds showed superior learning in the receptive task. These two studies are consistent with expectations based on DMN development from age 2–3 years.

An object retrieval study with 30- and 36-month-olds provided only qualified support for this conclusion. The experiment compared receptive video observation of a hiding event (3 objects in 7 possible hiding places) to an interactive screen condition in which button presses revealed the locations of the objects (Lauricella, Pempek, Barr, & Calvert, 2010). Consistent with the transfer deficit at this age, object retrieval performance was superior in an unmediated condition (directly observing a person hiding the objects) compared to the two screen conditions, especially in the younger group. Comparing the receptive video to the interactive screen condition, object retrieval was superior in the interactive condition, again especially in the younger age group (a mean difference of 0.58 for the 30-month-olds, versus 0.34 for the 36-month-olds). In this task, although the interactive screen condition produced performance superior to the receptive screen condition at both ages, perhaps due to increased focused attention to the specific hiding locations leading to improved associative learning, the reduction of this difference with age is consistent with increased DMN activation in the older children.

Moser et al. (2015) demonstrated the solution of a jigsaw puzzle to 30- and 36-month-olds either on a magnetic board where the pieces could be slid by hand, or a drag and drop touchscreen, or a receptive video demonstration (without a live person demonstrating how to do the task). They looked at transfer (using either a near or far transfer task) to the magnetic board or to the touchscreen versions of the task. The interactive tasks using a live demonstrator allowed better transfer than the receptive task (thus showing that the toddler transfer deficit persisted up to age 3 years), and the transfer deficit was symmetrical across platforms. With respect to the receptive video demonstration, 30-month-olds showed no transfer, whereas 36-month-olds showed transfer equivalent to the other conditions. All these results are consistent with maturation of the DMN over this age range as well as the instantiation of DMN function by means of live social interactions in the live demonstration conditions. Taken together, all available studies suggest an advantage of interactive screens over receptive screens for younger two-year-olds, with this advantage diminishing or reversing for toddlers approaching their third birthday. The findings are consistent with the younger toddlers being less able to utilize sequential/temporal comprehension and learning functions associated with the DMN.

Preschoolers. Once the DMN is reasonably well established, it continues to strengthen well into adulthood. We should begin to see more consistent learning and comprehension differences between interactive and receptive media consistent with the differences we have hypothesized. A study with children ranging in age from 2 to 4 years assessed vocabulary learning from a touch screen tablet program compared to a receptive video (presented on the tablet) of an unseen (“ghost”) player of the same program (Russo-Johnson, Troseth, Duncan, & Mesghina, 2017). Children used a word learning app in two interactive groups (tapping or drag and drop) and one receptive group watching the app events as if part of a video. The app presented a simple story via audio (personified objects with novel names wanting to cross a river). Children could “help” the objects cross the river either by tapping or dragging the objects, or simply by watching the objects cross by themselves. In each case, the objects were labeled by accompanying audio. Subsequent testing included both identifying objects on the screen and transfer tests to 3D “real” objects (only 4-year-olds were able to show transfer to 3D objects). Not surprisingly, older children showed better word learning than younger children, so the authors chose to use age as a control variable; this is unfortunate for present purposes insofar as we would predict a statistical interaction as a function of age with relatively more improvement from 2 to 4 years in the receptive condition. The reported results (controlling for age) revealed interactions with child sex. For boys the receptive video (watch only) condition was superior to the two interactive conditions. For girls, the drag condition was superior to the other two conditions. This study establishes that interactive versus receptive modes do in fact produce differential learning for particular subgroups of children of preschool age. We do not have any hypotheses or explanations of the observed gender differences.

An experiment with 4- and 5-year-olds provides a clearer test of our hypothesis. Children were given a lesson in measurement using non-standard units of measurement presented either interactively via touch screen tablet or by non-interactive video (Aladé, Lauricella, Beaudoin-Ryan, & Wartella, 2016). A character "Murray" works at the zoo and needs to measure the animals but forgot his measuring tool. The children were asked to measure animals' height and width using non-standard measurement tools (e.g., how many baseball bats high is a giraffe). The touch screen program allowed children to drag and drop objects onto a scaffolding line to determine the correct answer. A receptive comparison group watched a video (on a touch screen tablet) that illustrated an unseen player playing the game. A control group played a different Murray game that did not involve measurement. A near transfer group was tested on a paper picture of an animal with scaffolding bar shown and with same-size Lego blocks as measuring tools. A medium transfer group was similarly assessed but the scaffolding bars were not shown. A far transfer group was shown a picture of a robot without the scaffolding bars. These transfer tests thus varied in how close the task was to the original depicted lesson.

On the near transfer task, children in the interactive condition performed marginally better than the video condition, and both groups performed better than the controls. On the medium transfer task, performance was equivalent between the two experimental conditions and both were better than the controls. On the far transfer task, the receptive video condition was better than the interactive condition which was not different than the control condition. These results are consistent with our hypothesis that interactive screen media enhance focused associative learning on the specific actions in relation to the specific objects in the interactive game, producing better near transfer, whereas the receptive presentation enhanced contextual learning and causal relationships over a larger time and space frame producing better far transfer. In effect, our argument is that receptive screen media encourage the viewer to extract relationships as they occur over the entire presentation but with less learning of specific associations. Interactive touch screens, on the other hand, are effective in encouraging the user to focus on specific associations tied to concrete contexts presented within a narrow time frame.

Schroeder and Kirkorian (2016) presented 3- to 5-year-olds touch screen games based on the TV program *Dinosaur Train,* an educational series that teaches scientific concepts. The games were focused either on number concepts or on the notion of growth. In a within-subjects design, children played one of the games (interactive condition) and watched a video of another child playing the other game (receptive condition). Children played the games by touching and/or dragging objects, receiving feedback from the game for correct and incorrect responses. After the media experiences, the children were tested on near and far transfer tests. Children in the receptive condition performed better than children in the interactive condition on all but one of the transfer tests (a near transfer test for which there was no difference).

Taken together controlled studies with young children that compared interactive video to receptive video found that when there was a difference in transfer, interactive video tended to benefit near transfer. The reverse was found for far transfer tests, especially in children older than about 2 ½ years. These differences are what would be expected if the interactive screen condition activates a focused attentional system, especially the DAN, thus enhancing specific task- and context-bound associative learning. The receptive video condition, on the other hand, should activate the DMN, enhancing the learning of temporal, spatial, and causal connections across the whole presentation but perhaps at the cost of rapid and effective learning of specific associations. Receptive screen media apparently allow children to abstract larger conceptual relationships compared to the interactive touch screen media.

Recall that in toddlers, social-interactive screen video, such as Skype, is more effective in teaching than purely receptive video. An interesting study used receptive video in which a character appeared to "break the fourth wall" and speak directly to the preschool child audience (similar to programs such as *Blue's Clues,* Anderson et al., 2000). The study compared this pseudo interaction condition to the more standard receptive video condition in which two characters speak to each other but do not address the audience. In both conditions the characters tried to teach object labels. It should be noted that in the first case, the pseudo interaction with the child did not have the real-time reciprocal contingency characteristics of truly social-interactive media. Krcmar and Cingel (2017) found that the pseudo interactive condition was superior to the purely receptive condition in teaching novel words. This study suggests that social facilitation can improve learning from receptive media even if the social interaction is illusory.

Older Children. While we found few studies comparing interactive and receptive screens in toddlers and preschoolers, we found none with older children with the exception of research on e-books, briefly described later. Available research concerning cross-platform programming does not compare learning platforms with respect to comparable content (e.g., Fisch, Lesh, Motoki, Crespo, & Melfi, 2014). Other studies compare one interactive condition with another, different, interactive condition (e.g., Kwok et al., 2016).

Adults. We found no studies with adults that compared receptive video to truly interactive digital video using comparable content. A semi-relevant line of research compares adult learning from receptive video compared to video that can be replayed, reversed, paused, slowed, sped up, and the like. Using a video that demonstrated how to tie sailor knots, Schwan and Riempp (2004) found faster learning if these control features were made available while watching the videos. Merkt and Schwan (2014) used an educational history video with and without interactive features including the ability to move to different parts of the video using a search index. They found no differences between the receptive and "enhanced" versions on an essay test of the video or on questions related to declarative knowledge of the content. They did find, however, that the indexed topics were more likely to be mentioned in the essay in the enhanced condition. In their literature review of other studies using this type of comparison, Merkt and Schwan (2014) suggested that enhanced control features may be of greatest benefit for relatively brief videos as well as procedural videos.

A somewhat relevant study with university students concerned the "gamification" of study conditions while DMN activity was monitored by means of fMRI. (Howard-Jones, Jay, Mason, & Jones, 2016). Ten study topics were created covering a variety of fields in the humanities and sciences. Each topic was taught by means of a static computer screen showing pictures and associated text. Multiple-choice questions covered "remembering, understanding, applying, evaluating, and analyzing" although these categories of questions were not analyzed separately. One group studied the material in a traditional manner including being presented with study questions and answers. A second group engaged in self-quizzing where correct answers earned points (partial gamification), and a third gamification study condition involved active competition with another student for points. The students were scanned by fMRI during the periods they were learning the material on each screen. It should be noted that as the screen stimuli did not differ between conditions, this was not a direct comparison of interactive versus receptive situations.

There was greater deactivation of DMN during the study periods in the gamification conditions. Because the study material was expository, and because the material was temporally static and tested by multiple-choice questions, our hypothesis predicts that DMN deactivation would be associated with greater learning of the specific content presented on each screen. This was indeed found insofar as the competitive game condition produced better multiple-choice performance than either the study only or partial gamification conditions. Additionally, gamification was associated with increased subjective engagement compared to the other conditions.

Deactivation of the DMN, therefore, was associated with greater learning of expository university-level study material tested by multiple-choice questions. We would argue that this greater learning was due to activation of focused attention networks and that the better learning in the gamification condition reflected greater associative memory of specific content in each study screen. It is possible, however, that greater DMN activity in the study-only condition reflected off-task mind wandering and consequently less learning of any kind.

e-books. Recall that in adults the DMN is activated when listening to stories or reading text (Honey et al., 2012; Lerner et al., 2011; Regev et al., 2013; Tikka, Kauttonen, & Hlushchuk, 2018). Research with preschoolers has compared comprehension and memory of enhanced e-books (e-books that include interactive hot spots on the screen) to paper books or to hearing the text read aloud either as a "read-to-me" feature of the e-book or as read by an adult (usually a parent). To the extent to which the narrative is coherent, we would expect that the DMN would be activated with both e-books and paper books. To the extent to which e-books demand focused responses or simply distract from the narrative, we would expect that paper books or non-enhanced e-books would be superior in supporting comprehension. Finally, social engagement of an adult reading to the child would further support activation of DMN and thus support preschooler comprehension. In a review of research with preschool children that compares e-books to paper books and to adult reading, Reich, Yau, and Warschauer (2016) report findings that are consistent with our predictions. In particular, when differences in comprehension have been found, they have generally been in favor of paper books and adults reading aloud to the children. With respect to older children, a meta-analysis of e-book studies found that e-book enhancements such as accompanying moving pictures and audio increased comprehension whereas interactivity such as touch screen hotspots decreased comprehension (Takacs, Swart, & Bus, 2015). This latter finding has been supported by research subsequent to the meta-analysis (e.g., Ross, Pye, & Randell, 2016). Our interpretation is that interactivity distracts the child from paying attention to the core narrative because it deactivates the DMN, thus rendering the narrative less coherent to the child. On the other hand, accompanying moving pictures and audio that are in direct support of the narrative and that do not require interaction are unlikely to produce deactivation of the DMN.

7. Summary of evidence

A substantial amount of brain network research indicates that the default mode network underlies processing of coherent narrative receptive screen media in adults and that this processing is strongly related to comprehension and recall of content, particularly with respect to the temporal structure of events. Behavioral research indicates that the development of attention to, and comprehension of, television is fully consistent with default mode cognition underlying TV viewing. There is almost no equivalent brain network research on interactive screen media, nor are there normative studies of the development of interactive screen use comparable to those for receptive screen media. That said, the limited amount of research that directly compares receptive and interactive media, mostly with children, yields findings consistent with our hypothesis. Interactivity fosters greater associative learning in a narrow temporal and spatial frame whereas receptivity fosters greater learning across a larger temporal and spatial frame. Interactivity fosters greater near transfer of learning and receptivity fosters greater far transfer. Less directly relevant studies, such as those employing e-books, are also largely consistent with the hypothesis. That said, the total amount of relevant research is small, especially with respect to older children and adults.

8. Implications for theory and practice

Although we have framed our hypothesis in neuroscience terms, that is, in terms of the activation and functional connectivity of brain networks, our hypothesis is consistent with psychological theory as applied to screen media. Fisch's (2000) capacity theory, as well as story grammar theory as they relate to comprehension (e.g., van den Broek et al., 1996), are fully compatible with what is known about the functioning of DMN. With respect to principles for educational content development, Fisch notes the importance of keeping education "on the plotline", minimizing the distance of educational content from the narrative structure. In the terms we employ here, his principles are techniques to minimize the likelihood of deactivation of the DMN.

Assuming our main hypothesis withstands direct tests, there are important implications for the development of educational digital screen content. If the goal is to help the learner grasp a large set of connected concepts, especially if the connections involve causality and context in space and time, then a receptive medium such as television is likely the better choice. If the goal is to help the learner to recognize and remember specific associations, such as animal facts with the name and image of the animal then an interactive application may be the better choice.

Beyond associative learning, interactivity may also be the better choice in situations involving real or simulated social interactions, procedural learning, and where egocentric spatial representation is an advantage (such as a surgery simulator). There are also procedural contexts in which interactivity is likely to be substantially better for the learner especially when behavioral choices are required, as in dealing with an emergency, repairing a machine, or creating a work of art. Training fast, automated responses in choice situations would also imply the use of interactive media. Of course, learning applications can be structured as combinations of movie-like cut scenes and interactive tasks, with the choice depending on the kind of learning the developer wishes to foster at each point in the program. The point we emphasize here is that there are principled reasons to choose interactive or receptive approaches in programming content to be learned. It is not always inherently better for the learning situation to be interactive or receptive, but rather, the choice depends on the educational goals of the program producer. This is particularly relevant when the producer is able to provide content on multiple platforms (Fisch, Damashek, & Aladé, 2016; Raybourn, 2014).

9. Concluding remark

As promised a dozen years ago (Anderson, Bryant et al., 2006), noninvasive physiological methods have produced new perspectives and findings on media use and its consequences. A major advance using these methodologies is the discovery of brain networks that provide an underlying architecture of psychological functioning. Part of that architecture is the default mode network which supports comprehension and attention in movie and television viewing and in narrative comprehension more generally. Depending on the type of activation, some kinds of learning are more likely to be facilitated than others. In particular, we have argued that receptive media enhance comprehension of temporal and objective spatial relationships, whereas interactive media enhance local stimulus-response-goal associative learning and egocentric spatial relationships. The question for educational media creators is not whether one medium is better, it is when is it better? The answer appears to depend on what it is that needs to be learned.

10. Cited reference search methodology

The articles and books cited here were chosen as relevant to the main hypothesis concerning the role of the default mode network in cognitive processing of receptive and interactive screen media. All articles deemed to be directly relevant were cited except where existing reviews and meta-analyses could be substituted for individual research articles (e.g., the section on e-books). Articles were cited regardless of whether they provided support for the hypotheses in this article. Neuroscience-based articles that focused on specific brain areas were excluded from consideration insofar as the concern here concerns brain networks involving multiple brain areas. The principle source for the literature search was Web of Science. Simple search terms were: DEFAULT MODE NETWORK; BRAIN NETWORKS; MEDIA

COMPARISONS; CROSS-PLATFORM; PLATFORM COMPARISONS; TELEVISION; COMPUTER; GAMES; INTERACTIVE MEDIA; MEDIA; COMPREHENSION; MEMORY; LEARNING; TRANSMEDIA; MOVIES; NATURALISTIC; COMPUTER USE; GAMING; ANTICORRELATION; FILM. Numerous combinations of these terms were employed, such as DEFAULT MODE NETWORK *AND* COMPUTERS; BRAIN NETWORKS *AND* GAMES; MEDIA COMPARISONS *AND* COMPREHENSION. Some combinations such as MOVIES AND TELEVISION were not deemed useful as they would yield a vast thousands of references that were unlikely to include relevant articles.

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