

CHAPTER 11

The effects of positive affect and arousal on working memory and executive attention

Neurobiology and computational models

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There is now overwhelming evidence that moderate fluctuations in feelings can systematically affect cognitive processing (for reviews, see Ashby, Isen, & Turken, 1999; Isen, 1993). For example, Isen and others have shown that mild positive affect, of the sort that people could experience every day, improves creative problem solving (e.g., Isen, Daubman, & Nowicki, 1987; Isen, Johnson, Mertz, & Robinson, 1985), facilitates recall of neutral and positive material (Isen, Shalke, Clark, & Karp, 1978; Nasby & Yando, 1982; Teasdale & Fogarty, 1979), and systematically changes strategies in decision-making tasks (Carnevale & Isen, 1986; Isen & Geva, 1987; Isen & Means, 1983; Isen, Nygren, & Ashby, 1988; Isen, Rosenzweig, & Young, 1991).

Recently, Ashby et al. (1999) proposed a neuropsychological theory of many of these results. Specifically, they assumed that some of the cognitive influences of positive mood are due to increased levels of dopamine in frontal cortical areas that result from the events eliciting the elevation in mood. The starting point for this theory is the huge literature on the neurobiology of reward (for reviews, see Beninger, 1983; Lieberman & Cooper, 1989; Wise, 1982; Wise & Rompré, 1989), which in humans, often induces positive affect. In fact, one of the most common methods of inducing positive affect in subjects is to administer an unexpected noncontingent reward (i.e., by giving an unanticipated gift), and there is consensus in the neuroscience literature that unexpected reward causes dopamine release from brain stem sites (for reviews, see, e.g., Beninger, 1991; Bozarth, 1991; Philips, Blaha, Pfaus, & Blackburn, 1992; Schultz, 1992).

The theory developed by Ashby et al. (1999) was purely neuropsychological. It described some of the neural pathways and structures (and neurotransmitter systems) that might participate in mediating the neural effects of positive affect and its influence on cognition -- with special emphasis on creative problem solving. In this chapter we describe a computational extension of that theory. The computational version is a connectionist network that successfully accounts for the effects of positive feelings on three creative problem solving tasks (i.e., word association, the Remote Associates Test, and the Duncker candle task). Although these include verbal and performance tasks and have different surface features, for each task the connectionist network we describe has the same architecture. In addition, the same parameter values are used to represent the mood effects of the control and positive affect groups in all three applications. The network also successfully accounts for the effects of amphetamines on a two-choice guessing task. This demonstration is important because amphetamines directly increase brain dopamine levels, and therefore, we postulate that in low doses, amphetamines should have some of the same effects as positive affect. On the other hand, amphetamines stimulate other neurotransmitter systems in addition to dopamine (e.g., norepinephrine), and so some important differences between amphetamines and positive affect are expected in some tasks and conditions.

A second goal of this chapter is to explore more fully the concept of *arousal*, which is closely related to positive affect, both empirically and theoretically. Generally, conditions that induce positive affect are also likely to increase arousal, and as we will see, like positive affect, arousal is thought to increase the level of certain neuromodulators in frontal cortical areas. Thus, a major challenge to understanding the neural effects of positive affect is to disambiguate its effects from those of arousal.

The next section briefly reviews the literature on the influences of positive affect on cognition, with a focus on its effects on creative problem solving. The third section reviews the dopaminergic theory of positive affect that was developed by Ashby et al. (1999). The fourth section presents and tests a computational model that was inspired by this theory. Next, we examine arousal, focusing on its neuropsychological underpinnings, its effects on cognition, and on how it is related to positive affect. Finally, we close with some brief conclusions.

Positive affect and creative problem solving

It is now well-recognized that positive affect leads to greater cognitive flexibility and facilitates creative problem solving across a broad range of settings (e.g., Aspinwall & Taylor, 1997; Carnevale & Isen, 1986; Estrada, Isen, & Young, 1995; Estrada, Young, & Isen, 1994; Fiske & Taylor, 1991; George & Brief, 1996; Greene & Noice, 1988; Hirt, Melton, McDonald, & Harackiewicz, 1996; Isen, 1987, 1993; Isen & Baron, 1991; Isen et al., 1985, 1987; Kahn & Isen, 1993; Mano, 1997; Showers & Cantor, 1985; Staw & Barsade, 1993; Staw, Sutton, & Pelled, 1994; Taylor & Aspinwall, 1996). This work suggests that positive affect increases a person's ability to organize ideas in multiple ways and to access alternative cognitive perspectives. In dozens of experiments supporting this conclusion, subjects were assigned randomly to either a neutral or positive affect condition, and positive affect was induced in a variety of simple ways, such as receiving a small unanticipated gift, watching a few minutes of a comedy film, reading funny cartoons, or experiencing success on an ambiguous task. This indicates that the effects can be prompted readily, by small things in people's lives.

A detailed examination of this literature is beyond the scope of this chapter. The interested reader should consult Ashby et al. (1999). Instead, we will focus only on those empirical results that will be modeled below. First, in word association, positive affect subjects have been shown to respond to neutral words (but not to negative words) with a broader range of first associates than control subjects (Isen et al., 1985). Similarly, in a study with young adolescents, positive affect increased verbal fluency, and children in the positive affect condition gave more category words and more unusual examples of the category than children in the neutral affect control condition (Greene & Noice, 1988). A similar finding, with adult subjects, was obtained recently by Hirt et al. (1996).

Second, positive affect has been shown to improve performance in several tasks that typically are used as indicators of creativity or innovative problem solving (Isen et al., 1987). In one of these, called Duncker's (1945) candle task, a person is given a candle, a box of tacks, and a book of matches, and is asked to attach the candle to the wall in such a way that it will burn without dripping wax on the floor or table. To solve the problem, the person can empty the box of tacks, tack the box to the wall, and then use the box as a platform for the candle. Thus, the person must use one of the items (the box) in an unaccustomed way -- a classic criterion of creativity (e.g., Koestler, 1964). This type of cognitive flexibility has also been referred to as "breaking set" or overcoming "functional fixedness" (Duncker, 1945; Wertheimer, 1945). A number of studies have shown that positive affect subjects perform significantly better than controls

on Duncker's candle task (Greene & Noice, 1988; Isen et al., 1987).

A third task that has been used to study the influence of positive affect on cognitive flexibility or creativity is based on the Remote Associates Test (Mednick, Mednick, & Mednick, 1964), which was designed in accord with S. Mednick's (1962) theory of creativity. In this test, which in its full form was designed to measure individual differences in creativity, subjects are presented with three words and a blank line and are asked to respond with a word that relates to each of the three words given in the problem. An example is the following:

MOWER ATOMIC FOREIGN _____.

(The correct answer is POWER.) Seven items of moderate difficulty from the Remote Associates Test have been used in the research on the influence of affect. Several studies have found that positive affect improves accuracy in this test, not only in college students, but also in a sample of practicing physicians (Estrada et al., 1994; Isen et al., 1987).

Note that we are not claiming that positive affect will improve performance on all cognitive tasks. In fact, there are reports that positive affect impairs performance on some tasks (Oaksford, Morris, Grainger, & Williams, 1996). For this reason, we focus on creative problem solving, where the data have been remarkably consistent.

The dopamine hypothesis of positive affect

Ashby et al. (1999) proposed that many of the cognitive effects of positive mood are due to increases in brain dopamine levels that co-occur with mild elevations in mood. There is much evidence supporting this hypothesis. First, of course, is the already mentioned fact that dopamine is released after an animal encounters an unexpected reward (e.g., Mirenowicz & Schultz, 1994; Schultz, 1992), and reward is closely associated with positive affect, at least in humans. Second, drugs that mimic the effects of dopamine (i.e., dopamine agonists) or that enhance dopaminergic activity, elevate feelings (e.g., apomorphine, cocaine, and amphetamines) (e.g., Beatty, 1995). Third, dopamine antagonists (i.e., neuroleptics), which block the effects of dopamine, flatten affect (e.g., Hyman & Nestler, 1993). Fourth, dopamine release and positive affect are both associated with increased motor activity (e.g., Hale & Strickland, 1976; Kelly, Seviior, & Iversen, 1975; Protais, Bonnet, & Costentin, 1983; Strickland, Hale, & Anderson, 1975).

Although Ashby et al. (1999) proposed that dopamine mediates the cognitive effects (or some of the cognitive effects) of pleasant feelings, several lines of evidence suggest that it does not mediate the pleasant feelings associated with positive affect. First, dopamine cells in the ventral tegmental area (VTA) of cats have been shown to fire to loud clicks and bright flashes of light that have never been paired with a reward (Horvitz, Stewart, & Jacobs, 1997). Second, stressful or anxiety-provoking events, which presumably would produce negative affect in humans, actually appear to increase dopamine levels in certain brain regions (i.e., prefrontal cortex) (Abercrombie et al., 1989; Cenci et al., 1992; Imperato et al., 1991; Sorg & Kalivas, 1993; Zacharko & Anisman, 1991). Finally, many researchers have argued that a primary function of dopamine is to serve as the reward signal in reward-mediated learning (e.g., Beninger, 1983; Miller, 1981; Montague, Dayan, & Sejnowski, 1996; White, 1989; Wickens, 1993). Thus, one possibility is that at least some of the results that purportedly link dopamine and reward are actually due to a failure of learning. Although these results do not disconfirm the hypothesis that dopamine release occurs during periods of positive affect, they do argue against the stronger hypothesis that dopamine release is responsible for initiating the pleasant feelings associated with positive affect.

Ashby et al. (1999) were also careful to point out that in addition to dopamine, other neurotransmitters and neuromodulators are known to influence mood and emotion. For example, theories of depression have long focused on norepinephrine and serotonin (e.g., Schildkraut, 1965). As a result, a complete theory of mood, and probably also a complete theory of positive affect, must consider many neurochemicals. Even so, Ashby et al. (1999) argued that to account for the influences of positive affect on cognition, the most important place to begin is with dopamine.

Ashby et al. (1999) developed the dopaminergic theory of positive affect in considerably more detail in the case of frontal cortical functioning. They postulated that during positive affect conditions, dopamine is released from the VTA into the prefrontal cortex and anterior cingulate. They further proposed that the dopamine projection into prefrontal cortex facilitates working memory, whereas the projection into anterior cingulate facilitates executive attention and the selection of cognitive perspective. There is growing consensus that prefrontal cortex is the key cortical substrate of working memory (a review is beyond the scope of this chapter; see, e.g., Fuster, 1989; Goldman-Rakic, 1987, 1995). There is also strong evidence that reductions in dopamine levels in prefrontal cortex cause working memory deficits (Brozoski, Brown, Rosvold, & Goldman, 1979; Gotham, Brown, & Marsden, 1988; Levin, Labre, & Weiner, 1989; Roberts et al., 1994; Williams & Goldman-Rakic, 1995). Data on the effects of

increases in prefrontal cortex dopamine levels suggest that moderate increases facilitate working memory, but large increases cause deficits – in other words, working memory performance is optimized at some intermediate dopamine level (Lange et al., 1992; Luciano, Depue, Arbisi, & Leon, 1992; Williams & Goldman-Rakic, 1995). Based on these data, Ashby et al. (1999) hypothesized that moderate, but not extreme levels of positive affect might improve working memory.

Posner and Petersen (1990; see, also Posner & Raichle, 1994) proposed that the anterior cingulate cortex is a key structural component of the anterior (i.e., executive) attentional system. Specifically, they hypothesized that the (dorsal) anterior cingulate is involved in the selection of cognitive perspective and in the conscious directing of executive attention. Ashby et al. (1999) reviewed evidence supporting this general model, and also that dopamine enhances these abilities. For example, dopamine antagonists impair cognitive set shifting (Berger et al., 1989), and patients with Parkinson's disease, which reduces brain dopamine levels, are impaired in tasks that require selection or set shifting (e.g., Brown & Marsden, 1988; Cools et al., 1984).

Ashby and his colleagues argued that the act of switching attention from one cognitive set to another involves two separate operations – first, a new cognitive set must be selected, and second, attention must be switched from the old set to the new one (Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Ashby et al., 1999). They also proposed, and presented evidence in support of the hypothesis that the selection operation is mediated cortically, by the anterior cingulate and possibly also by the prefrontal cortex, and that switching is mediated by the head of the caudate nucleus. A complete review of this evidence is beyond the scope of this chapter (i.e., see Ashby et al., 1998, 1999). However, we will briefly mention a few results supporting this general model of executive attention. First, a recent neuroimaging study identified the (dorsal) anterior cingulate as the site of hypothesis generation in a rule-based category-learning task (Elliott, Rees, & Dolan, 1999). Second, lesion studies in rats implicate the dorsal caudate nucleus in rule switching (Winocur & Eskes, 1998). Third, injections of a glutamate agonist directly into the striatum increase the frequency with which cats switch from one motor activity to another in a task where food rewards are delivered for such switching behaviors (Jaspers, De Vries, & Cools, 1990a, 1990b).

Finally, lesioning the dopamine fibers that project from VTA into the prefrontal cortex *improves* the performance of monkeys in an analogue of the Wisconsin card sorting test, even though it impairs their spatial working memory

(Roberts et al., 1994). If switching occurs in the prefrontal cortex, then such lesions should impair switching performance (as seen, e.g., in Parkinson's patients). If the switching occurs in the basal ganglia, then one's first thought might be that lesioning dopamine fibers in the prefrontal cortex should have no direct effect on switching. However, it turns out that such lesions increase dopamine levels in the basal ganglia (Roberts et al., 1994). Therefore, if the basal ganglia are responsible for switching, and if switching is enhanced by dopamine, then lesioning dopamine fibers in prefrontal cortex should improve switching, which is exactly what Roberts et al. (1994) found.

Ashby et al. (1999) proposed that much of the improvement in creative problem solving that is observed under conditions of positive affect is due to the facilitation of the executive attention system that occurs with increased dopamine release into the anterior cingulate cortex. We will next test this hypothesis more rigorously by implementing it within a connectionist model of some common creative problem solving tasks, and ask whether the model can account for the known effects of positive affect on performance in these tasks.

A connectionist model of creative problem solving

In this section we describe and test a general connectionist model of mental flexibility in creative problem solving tasks that makes specific predictions about any experimental manipulation that increases brain dopamine levels, including positive affect. We focus on three tasks that were described in an earlier section, and that are known to be affected by positive feelings. The first is word association, in which the subject is presented with a stimulus word and then responds with the first word that comes to mind. As described above, Isen et al. (1985) found that positive affect subjects were more likely to respond with unusual first associates (54% of total responses) compared to neutral affect subjects (39% of responses), where unusualness was defined by the Palermo and Jenkins (1964) word association norms. In addition, subjects in the positive affect condition showed greater diversity in their responses than did those in the control group.

The second task is the Remote Associates Test (Mednick et al., 1964), in which subjects are presented with three cue words and are asked to find a fourth word that is related in some way to each of the three cue words. For example, one set of cue words is *gown*, *club*, and *mare*. In this case, the correct response is *night* (i.e., *nightgown*, *nightclub*, and *nightmare*). As mentioned previously, Isen et al. (1987) found that positive affect subjects were significantly more

accurate on a subset of moderately difficult items from the Remote Associates Test than neutral affect subjects (63% correct versus 50% correct).

The third task is Duncker's (1945) candle problem, in which subjects are given a box of tacks, a book of matches, and a candle, and are asked to attach the candle to the wall and light it in such a way that no wax drips on the floor. Isen et al. (1987) found that positive affect subjects were significantly more accurate (58% correct) on the candle problem than neutral affect controls (13% correct).

In the candle task, success is more likely if the subject overcomes the dominant cognitive set (viewing the box as a container) and selects a set that is less typical (viewing the box as a platform). If dopamine enhances the ability of the executive attention system to select more flexibly, then it seems reasonable to expect positive affect to improve performance in the candle task. We hypothesize that such selection effects could also influence performance in the word association and remote associates tasks. For example, in the Remote Associates Test, to produce the word *night* when presented with the cue words *club*, *gown*, and *mare*, the subject must overcome the dominant cognitive set that the correct response is semantically related to the cue words. Instead, the subject must consider alternative ways in which the words may be related, such as by being part of a compound word.

It is also easy to imagine situations in which the selection of unusual or nondominant cognitive sets would lead to unusual responses in the word association task. For example, consider a trial on which the stimulus word is *pen*. To respond, the subject must select among the various meanings of this word. The dominant interpretation (or set) is of *pen* as a writing implement. In this case, the subject is likely to respond with a high frequency associate, such as *pencil* or *paper*. A more unusual interpretation is of *pen* as a fenced enclosure. A subject who selects this interpretation is likely to respond with a low frequency associate, such as *barn* or *pig*. Thus, it is possible that the effects of positive feelings on the word association, remote associates, and candle tasks are all due to a common phenomenon — namely, that positive affect is associated with increased dopamine release into anterior cingulate, which increases the flexibility of the executive attention system.

A connectionist model that instantiates this hypothesis is shown in Figure 1. This model was proposed by Ashby, Turken, and Isen (1996), who called it the creative problem solver. The alternative cognitive sets are represented by the units P1 and P2 in prefrontal cortex. For example, in the word association task when the stimulus word is *pen*, P1 might represent *pen as a writing implement* and P2, *pen as a fenced enclosure*. The anterior cingulate selects one of the

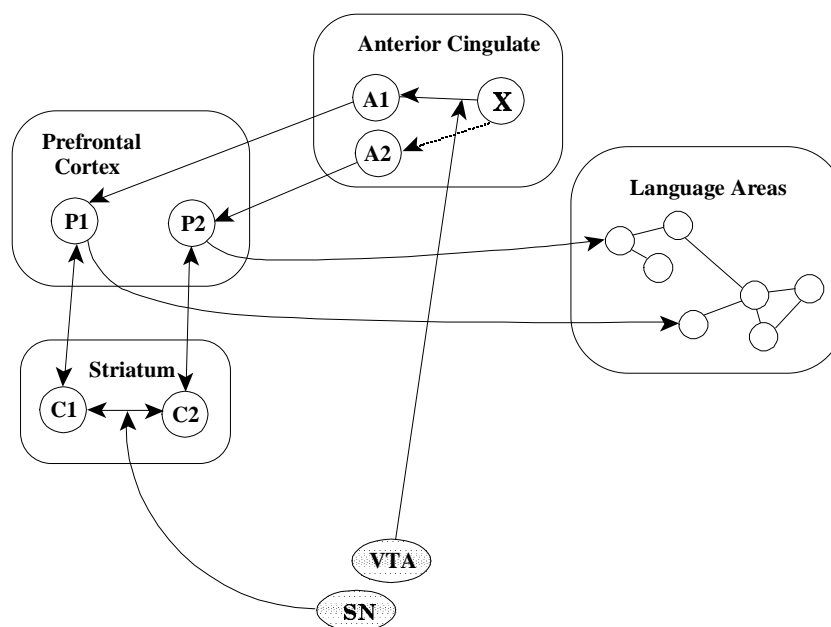


Figure 1. Computational architecture of the creative problem solver connectionist network (SN = Substantia Nigra, VTA = Ventral Tegmental Area).

cognitive sets via the units X, A1, and A2. If P1 is the dominant set and the anterior cingulate is able to overcome this dominance and select P2, then the switching is accomplished via lateral inhibition in the caudate nucleus between units C1 and C2. Next, each of the cognitive set units (i.e., P1 and P2) projects back to a different semantic network in some cortical language area (presumably in the temporal lobe). For example, P1 presumably projects to a network that includes the words *paper* and *pencil* and P2 to a network that includes *barn* and *pig*.

Neuroimaging data support this general model. For example, Frith, Friston, Liddle, and Frackowiak (1991a) used PET scanning to examine cortical activity in normal adults during word fluency and lexical decision tasks, as well as a number of control tasks. Relative to the control tasks, they found increased activation in anterior cingulate and (dorsal lateral) prefrontal cortex in the semantic tasks, and either increased or decreased activation in the temporal language areas, depending on the type of semantic task. Based on these results, Friston, Frith, Liddle, and Frackowiak (1991) postulated that in semantic tasks involving selection or generation, the prefrontal cortex modulates activity in temporal language areas via (glutaminergic) cortico-cortical projections. Frith, Friston, Liddle, and Frackowiak (1991b) generalized this hypothesis to nonsemantic tasks. Specifically, they proposed that in many tasks requiring

“willed action”, the prefrontal cortex modulates activity in remote, but task relevant, cortical areas. We adopt the Frith et al. (1991b) assumption here. Later in this section, we simulate the performance of the creative problem solver in two nonsemantic performance tasks (i.e., the Duncker candle task and a two-choice guessing task). In these cases, we assume the relevant cortico-cortical projections are from the cognitive set units in prefrontal cortex (e.g., P1 and P2 in Figure 1) to specific motor units in premotor or motor cortex.

We assume the dopamine projection from VTA into cingulate enhances the ability of the cingulate to overcome the dominant set, but in a connectionist network we must be precise about the effect of increasing dopamine levels in the cingulate. Some dopamine is present even in the neutral affect conditions, so the effect of positive mood must be to alter activation patterns in the anterior cingulate, rather than to initiate any new processing. The question then, is how might dopamine modulate activation functions in a connectionist network? The next section proposes an answer to this question.

A dopamine modulated activation function

After studying data on the firing rates of striatal cells, Servan-Schreiber, Printz, and Cohen (1990) proposed that dopamine in the prefrontal cortex increases the gain of a standard logistic activation function. Let A_k represent the output activation of unit k and let a_i represent the activation of the i th unit that feeds into unit k . Then the logistic activation function (e.g., Rumelhart & McClelland, 1986) assumes

$$A_k = \frac{1}{1 + e^{-(\alpha_k \sum_i w_{ik} a_i) + \beta_k}} \quad (1)$$

where w_{ik} is the weight connecting units i and k , and α_k and β_k are the gain and bias on unit k , respectively. Servan-Schreiber et al. (1990) assumed that increasing the amount of dopamine into unit k increases the gain α_k . Figure 2 illustrates this model for two different dopamine levels. In this model, dopamine has two effects on activation. First, when dopamine levels are increased, the slope of the activation function increases. Second, activation functions associated with different dopamine levels cross. Thus, when the net input to unit k is small (i.e., when there is little overall stimulation), dopamine has an inhibitory effect on output activation. However, when the net input is large (as when there are many sources of stimulation or the stimulation is intense), the effects of dopamine are excitatory. Cohen and Servan-Schreiber (1992) used this model to construct

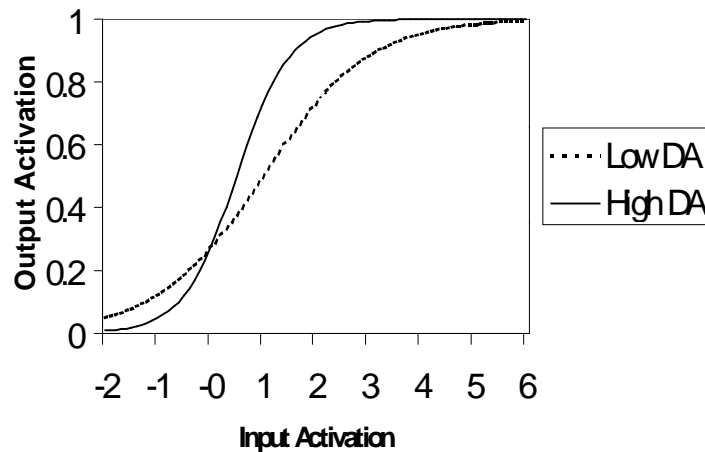


Figure 2. Activation functions assumed by Servan-Schreiber, Printz, and Cohen (1990). The effect of dopamine is to increase the slope of the activation function.

connectionist networks to account for the behavioral deficits of schizophrenics in several different cognitive tasks.

A somewhat different model was proposed by Ashby and Casale (under review), who derived their model from standard pharmacological techniques. The two most important assumptions of this technique are that the magnitude of the tissue response is proportional to the concentration of the final product of the chemical reaction, and that the tissue response is determined after chemical equilibrium is reached. The nature of the final product depends on whether the drug (e.g., the neurotransmitter) activates a second messenger system. If it does (e.g., as is the case with dopamine) then the final product is the concentration of activated second messenger.

There are two classes of dopamine receptors. The D_1 class includes the D_1 and D_5 receptors, and the D_2 class includes the D_2 , D_3 , and D_4 receptors (e.g., Seeman & Van Tol, 1994; Sibley, Monsma, Jr., & Shen, 1993). Of these, the D_1 and D_2 receptors are, by far, the most common, and in frontal cortical areas, there are approximately ten times as many D_1 as D_2 receptors (Lidow, Goldman-Rakic, Gallagher, & Rakic, 1991). For this reason, Ashby and Casale focused on the D_1 receptor, which is a so-called Class II (i.e., slow acting) receptor that is linked to a G protein that acts to increase intracellular levels of cAMP (e.g., Cooper, Bloom, & Roth, 1991; Strange, 1988).

There is now substantial evidence that dopamine modulates the effects of glutamate through the D_1 receptor (e.g., Cepeda, Radisavljevic, Peacock, Levine, & Buchwald, 1992; Smiley, Levey, Ciliax, & Goldman-Rakic, 1994). Glutamate is an excitatory neurotransmitter with two classes of receptors — NMDA and

non-NMDA (e.g., Hyman & Nestler, 1993). At low levels of stimulation, the glutamate response is dominated by activity at non-NMDA (e.g., AMPA) receptors. At high levels of stimulation, the glutamate response is dominated by activity at NMDA receptors. Recent evidence indicates that dopamine increases the efficacy of glutamate by prolonging the action of the Ca^{2+} second messenger that is activated when glutamate binds to the NMDA receptor (Hemmings, Walaas, Ouimet, & Greengard, 1987; Pessin et al., 1994; Wickens, 1990, 1993).

Cepeda et al. (1992) applied selective NMDA and non-NMDA glutamate agonists *in vitro* to human cortical tissue, both in the presence and absence of dopamine. As predicted, they found that dopamine enhanced the tissue response to NMDA agonists. However, they also found that dopamine depressed the tissue response to non-NMDA agonists. The mechanism through which dopamine inhibits the glutamate response through non-NMDA (e.g. AMPA) receptors is unknown. When deriving the activation function, however, the nature of this mechanism is relatively unimportant. Therefore, Ashby and Casale assumed that dopamine decreases the affinity of glutamate for non-NMDA receptors.

Let A_k denote the overall output activation of unit k , and let $A_{k,AMPA}$ and $A_{k,NMDA}$ denote the activations produced through the AMPA (i.e., non-NMDA) and NMDA channels, respectively. Then from the assumptions described above, Ashby and Casale proposed that:

$$A_k = e^{-\theta(A_{k,AMPA} + A_{k,NMDA})} A_{k,AMPA} + [1 - e^{-\theta(A_{k,AMPA} + A_{k,NMDA})}] A_{k,NMDA}, \quad (2)$$

for some positive constant θ . The two channel activation functions are defined as

$$A_{k,AMPA} = \frac{\sum_i w_{ik} a_i}{\sum_i w_{ik} a_i + K_{AMPA}(DA)} \quad (3)$$

and

$$A_{k,NMDA} = \frac{1}{1 + K_E(DA) \left(1 + \frac{K_{NMDA}}{\sum_i w_{ik} a_i} \right)}. \quad (4)$$

$K_{AMPA}^{-1}(DA)$ is the affinity of glutamate for the AMPA receptor. As mentioned above, dopamine inhibits the action of glutamate through non-NMDA receptors, so $K_{AMPA}(DA)$ is assumed to increase with dopamine level. On the other hand, $K_E^{-1}(DA)$ is proportional to the efficacy of the glutamate response through the NMDA channel. Since dopamine facilitates this glutamate response, $K_E(DA)$ is

assumed to decrease with dopamine level. Finally, K_{NMDA}^{-1} is the affinity of glutamate for the NMDA receptor.

Figure 3 shows plots of the activation function defined by Equations 2 - 4 for two different dopamine levels. Note that the Ashby and Casale (under review) model confirms the intuition of Servan-Schreiber et al. (1990) about two key properties of the effects of dopamine on activation functions. First, the activation functions in Figures 2 and 3 both show steeper slopes with increasing dopamine levels. Second, the activation functions in both figures cross. In both cases, dopamine is inhibitory at low levels of input activation and excitatory at high levels. The most striking difference between the two functions is in asymptotic activation levels. The Servan-Schreiber et al. model assumes that large input activations drive the unit to saturation for all dopamine levels. In contrast, the Figure 3 model assumes saturation is virtually never reached and that increasing dopamine levels substantially increases asymptotic activation. According to the pharmacological theory used by Ashby and Casale, saturation occurs only when every receptor molecule and every second messenger molecule in the tissue are activated. These conditions are virtually impossible to meet, so saturation is essentially impossible.

Tests of the model

The Ashby et al. (1996) general connectionist model of cognitive set selection and switching (i.e., the creative problem solver) is illustrated in Figure 1, and the effects of dopamine on activation produced within the anterior cingulate (and prefrontal cortex) are modeled by Equations 2 - 4. Before determining whether this model could account for the influence of positive affect on creative

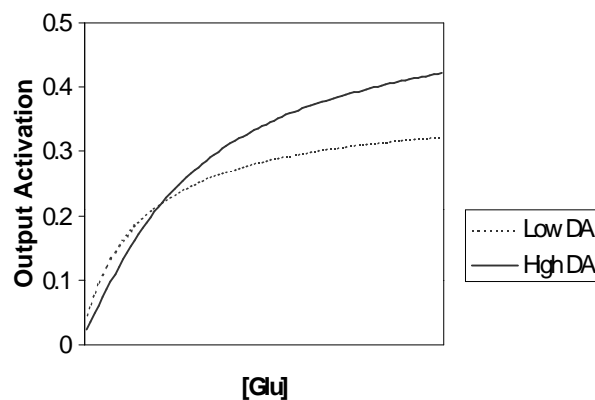
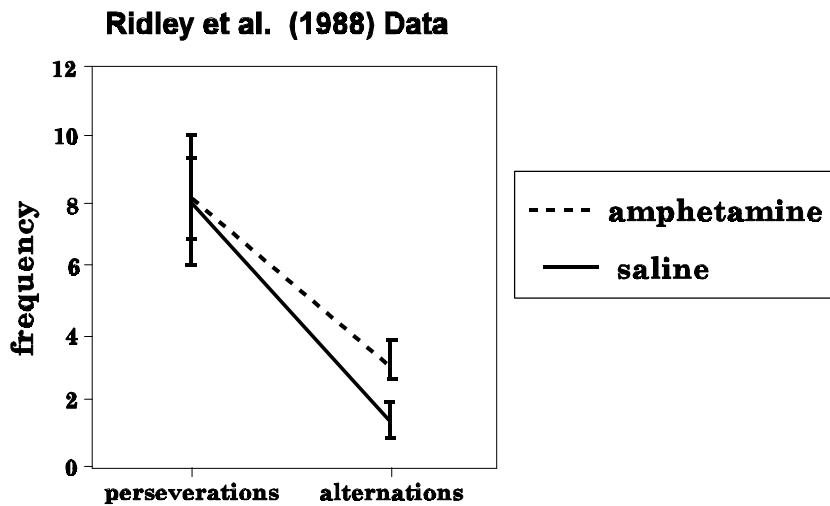


Figure 3. Activation functions assumed by Ashby and Casale (under review).

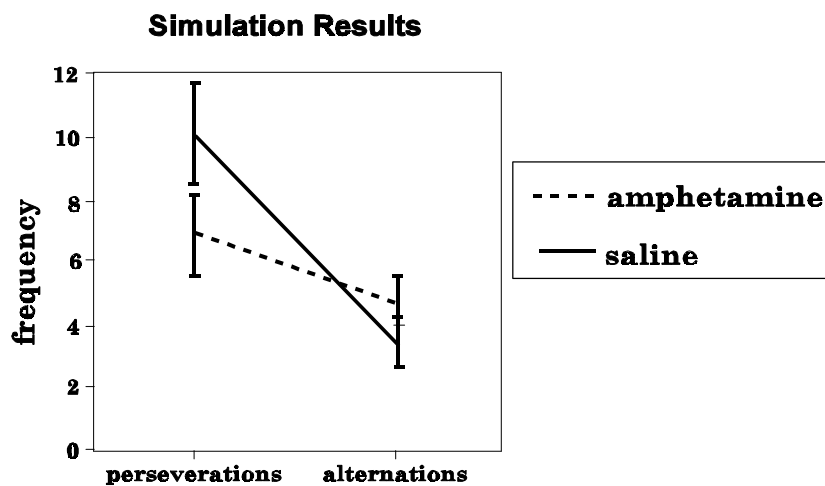
problem solving, Ashby et al. (1996) applied it to data from an experiment where brain dopamine levels were directly manipulated. Specifically, this application asked whether the model could account for the effects of amphetamines (which, among other effects, increase dopamine release) on a probability learning task reported by Ridley et al. (1988). Amphetamines are known to stimulate other neurotransmitters as well as dopamine (e.g., norepinephrine), and thus the model described in this section does not provide a complete description of the effects of amphetamines on cognition. Also, we do not expect positive affect to have the same effects as amphetamines in all cognitive tasks, even though they may have some of the same effects because of the dopamine release associated with each.

Two-Choice Guessing. Ridley et al. (1988) had two groups of normal (human) adults participate in a standard probability learning task (e.g., see, Estes, 1976). Prior to the task, one group was administered amphetamines and the second control group was given a saline solution. On each trial, two identical boxes appeared and the subjects were asked to guess which one contained a target. The target was equally likely to appear in either the right (R) or the left (L) box, so there is no strategy that guarantees greater than chance accuracy. Ridley et al. arbitrarily defined a perseveration as guessing the same box four times in a row (i.e., either responding *RRRR* or *LLLL*) and an alternation as successively switching on four consecutive trials (i.e., either responding *RLRL* or *LRLR*). The results are summarized in Figure 4a (averaged across subjects). With the Ridley et al. design, completely random responding leads to an average of 5 perseverations and 5 alternations. These data are characterized by the following three qualitative properties: (1) both groups showed more perseverations than expected by chance, (2) both groups showed fewer alternations than expected by chance, and (3) the amphetamine group had significantly more alternations than the control group, which caused an interaction between condition (saline versus amphetamine) and response type (perseveration versus alternation).

A similar increase in alternation responses has been reported under positive affect conditions, as one component of a more general increase in variety seeking (Kahn & Isen, 1993, Experiment 1). Amphetamines are well known to have similar effects on a wide variety of behaviors. Evenden and Robbins (1983) summarized the effects of amphetamines as follows: “responses occurring with a high probability . . . are reduced by the drug, whereas responses occurring with a lower probability may be increased” (p. 72). Of course, one consequence of such an effect is that under amphetamines, subjects should be more likely to adopt an unusual or nondominant cognitive perspective (or set). This result



a)



b)

Figure 4. Results from the two-choice guessing experiment of Ridley, Baker, Frith, Dowdy, and Crow (1988) (Figure 4a) and from simulations of this experiment by the creative problem solver connectionist network (Figure 4b).

supports the hypothesis that amphetamines do not simply increase arousal, since arousal has long been known to facilitate dominant, not innovative responding.

On the surface, this experiment appears quite different from the tasks for which the creative problem solver (i.e., the Figure 1 connectionist network) was developed. Even so, only minor modifications need to be made to the Figure 1

network to account for the Ridley et al. (1988) results. In particular, Ashby et al. (1996) assumed the units A1 and P1 correspond to one response (say, response *R*) and units A2 and P2 correspond to the other (response *L*). Rather than project to temporal language areas, they assumed units P1 and P2 project directly to the relevant motor areas in premotor and motor cortex (the cortico-striatal-pallidal-thalamic loops could still be operative). Given this slight modification, the behavior of the creative problem solver in the Ridley et al. (1988) task was simulated. Subjects were assumed to have no initial bias toward either response. After a correct guess, the habit strength associated with that particular response was increased, which raised the probability that the same response would be chosen on the next trial. Following an error, the habit strength associated with the incorrect response was decreased. Technical details of all simulations are described in the Appendix.

The results of the simulations are shown in Figure 4b. The predicted values were obtained by averaging across 1000 replicated simulations of the experiment. Figure 4b also shows predicted error bars. These were generated by computing the standard deviation in the predicted frequencies over the 1000 replications. The resulting standard deviations were then divided by $\sqrt{12}$, since Ridley et al. (1988) used 12 subjects in each experimental condition. The creative problem solver displayed all three qualitative properties seen in the human data. Specifically, both simulated groups showed more perseverations than expected by chance and fewer alternations, and there was an interaction between condition and response type. In addition, the predicted error bars were close to the error bars observed by Ridley et al. (1988). The only real deviation between the model and the data was that the creative problem solver predicted a few more perseverations for the saline group than were observed by Ridley et al. (1988). Overall, the model was quite successful at accounting for the effects of amphetamine on two-choice guessing (especially given that no real attempt was made to maximize goodness-of-fit).

Word Association. Next, consider the ability of the model to account for the influence of positive affect on creative problem solving. Ashby et al. (1996) simulated the performance of the creative problem solver in the word association task, the Remote Associates Test, and the Duncker candle task. Across the three tasks they assumed one dopamine level for the neutral affect control condition and another higher level for the positive affect condition¹.

Recall that Isen et al. (1985) found that positive affect subjects were more likely to respond with unusual associates in a word association task than neutral affect subjects (54% versus 39%). Ashby et al. (1996) simulated the performance

of the creative problem solver in a word association task in which the stimulus word was *palm*. For illustrative purposes, they assumed the most common response of a neutral affect control subject to be *hand*, followed in order of decreasing frequency by *finger*, *sweaty*, *tree*, *Hawaii*, *reader*, *steal*, *lift*, and *basketball*. The creative problem solver model for this particular example is shown in Figure 5. In this example, the cognitive set units in prefrontal cortex correspond to the alternative interpretations of *palm*, as a *part of the hand*, as a verb describing a *use of the hand*, or as a component of a *compound word*. Each of these units then projects back to a different semantic network in the temporal language area.

The performance of the creative problem solver in this task is illustrated in Figure 6. There are no published data that allow us to specify the semantic networks associated with the various alternative interpretations of *palm* (i.e., including the architecture and the numerical values of all weights between nodes). Therefore, when constructing the version of the creative problem solver shown in Figure 5, Ashby et al. (1996) chose the various weights so the network

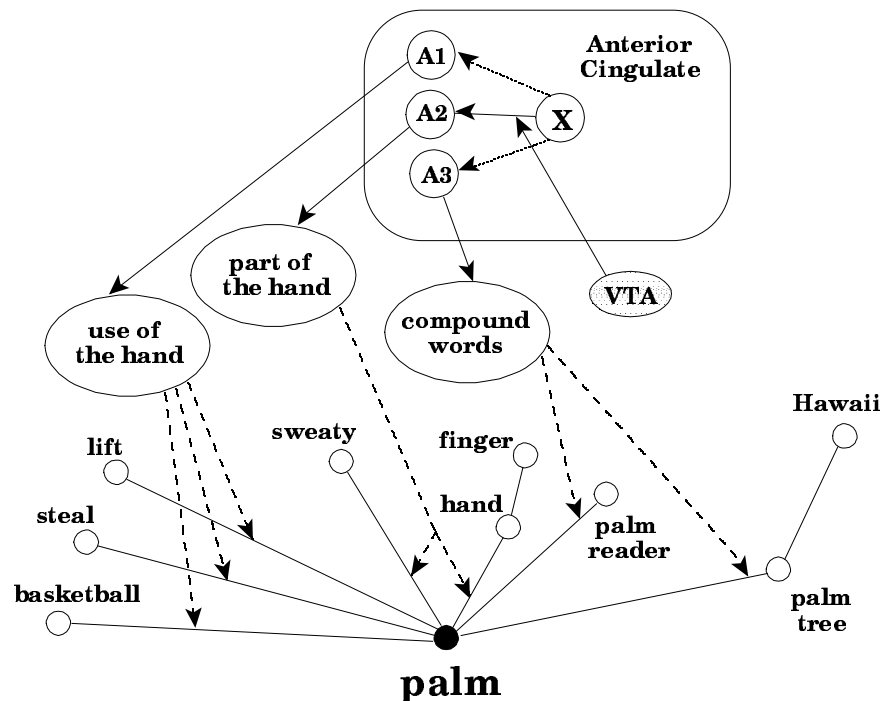


Figure 5. The computational architecture assumed by the creative problem solver connectionist network for a trial of the word association task in which the stimulus word is *palm*.

would reproduce the ordinal relations among the responses assumed in our illustration. As a result, the network could mimic any set of data that could be collected in the neutral affect control condition. However, once the weights are fixed in this manner, the predictions for the positive affect condition are also fixed². Therefore, the true test of the model is not whether it can account for the data from the control condition, but whether it correctly predicts the relation between the control and positive affect data.

In agreement with the Isen et al. (1985) results, note that the creative problem solver correctly predicts that the first-associate response proportions for the positive affect subjects are higher for all unusual associates (and therefore, necessarily lower for the most common response). The Isen et al. (1985) data and the creative problem solver both agree that the most common associate is not necessarily lost or unavailable to the positive affect subjects. Instead, both the data and the model suggest that other responses are also cued, so that the dominant response becomes somewhat less dominant than it is under neutral affect conditions, and less typical responses become relatively more accessible.

Remote Associates Test. Among the most reliable effects of positive mood is that it improves performance in the Remote Associates Test (e.g., Estrada et al., 1994; Isen et al., 1987). For example, Isen et al. (1987) found that positive affect improved performance in that test by 13% (from 50% to 63%) when the test items were of moderate difficulty. On one trial of this study, subjects were

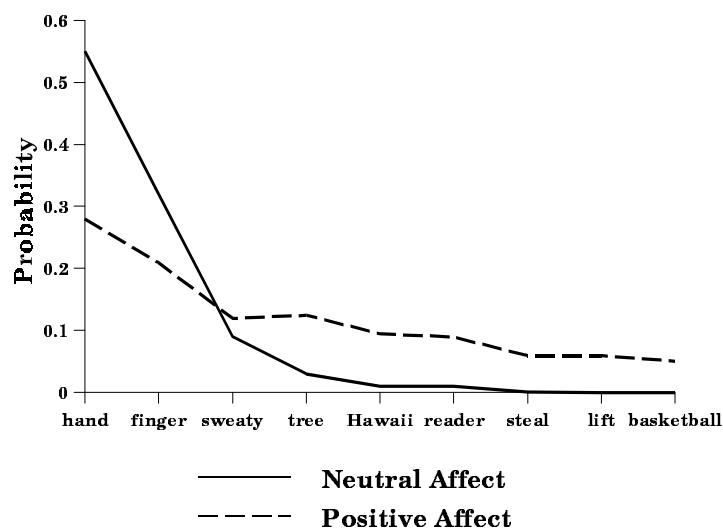


Figure 6. Simulated data from the creative problem solver connectionist network for a trial of the word association task in which the stimulus word is *palm*.

presented with the cue words *gown*, *club*, and *mare*. In this case, the correct response is *night*. Ashby et al. (1996) simulated the performance of the creative problem solver on this trial of the Remote Associates Test by using the architecture shown in Figure 7. Here two relevant cognitive sets are that the correct response is a word that is *semantically* related to the cue words, or that it might be part of a compound word with each of the cue words. In the former case, likely responses are words like *dance* or *party*, but the correct response will be discovered only if the latter cognitive set is adopted. The results of the simulations are illustrated in Figure 8. Note that in agreement with the empirical literature, accuracy is substantially higher in the positive affect condition (since the correct response is *night*).

This version of the model is overly simple for at least two different reasons. First, it almost surely oversimplifies the representation of alternative cognitive sets or perspectives for this problem. A more realistic model would show many more alternative perspectives. Nevertheless, the performance of a version with more alternative cognitive sets would be qualitatively similar to the performance of the Figure 7 version. Second, the model shown in Figure 7 is a feedforward connectionist network. As such, it ignores the temporal dynamics of the problem

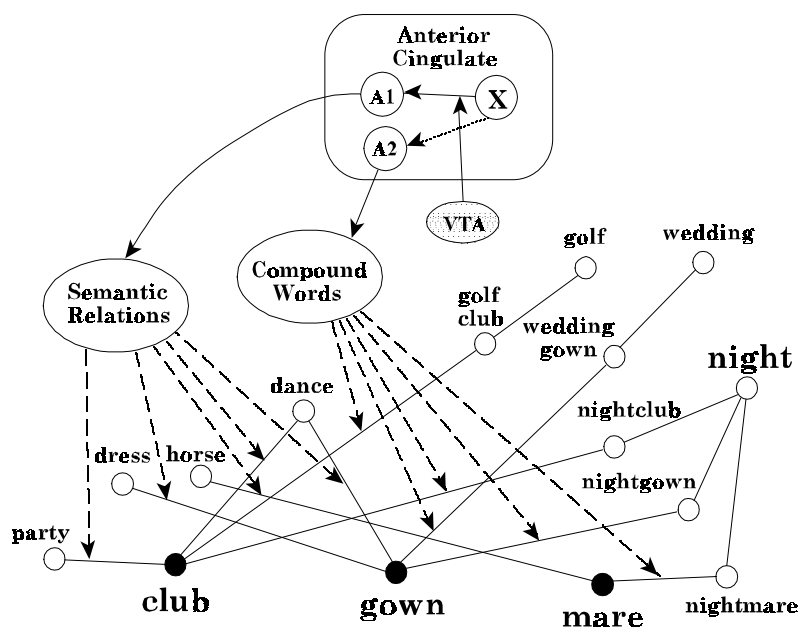


Figure 7. The computational architecture assumed by the creative problem solver connectionist network for a trial of the remote associates task in which the stimulus words are *gown*, *club*, and *mare*.

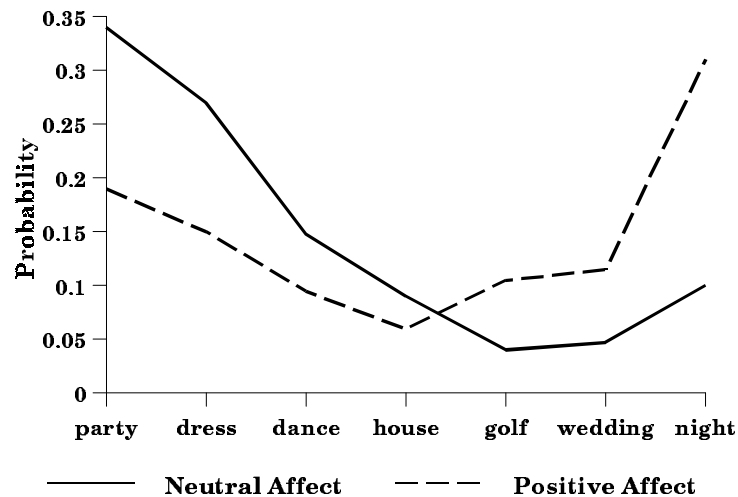


Figure 8. Simulated data from the creative problem solver connectionist network for a trial of the remote associates task in which the stimulus words are *gown*, *club*, and *mare*.

solving process. A human subject who failed initially to solve the problem might try again. It is straightforward to generalize the network in this fashion; that is, to make it recurrent. In fact, the version of the creative problem solver that Ashby et al. (1996) applied to the Duncker candle task is recurrent (see the next subsection). However, because of the uncertainty as to the true nature of the semantic networks that are accessed during the Remote Associates Test, little is gained by making the Figure 7 network recurrent.

Duncker Candle Task. Isen et al. (1987) found that a positive affect group was successful in the Duncker candle task much more frequently than the neutral affect control group (58% versus 13% correct). The network architecture of the creative problem solver when applied to the candle task is shown in Figure 9. Here the dominant cognitive set is to view the box as a container for the tacks. To solve the problem, the subject must switch away from the dominant set and view the box as an independent object that might serve as a potential platform for the candle. Once a set or perspective is selected, the motor actions that follow are predetermined. Thus, in the creative problem solver, the cognitive set units project to units in the premotor and motor cortices that are associated with specific motor actions. To this point, then, the network is identical to the version of the creative problem solver that Ashby et al. (1996) used to model the Ridley et al. (1988) two-choice guessing task. In the candle task, however, a subject

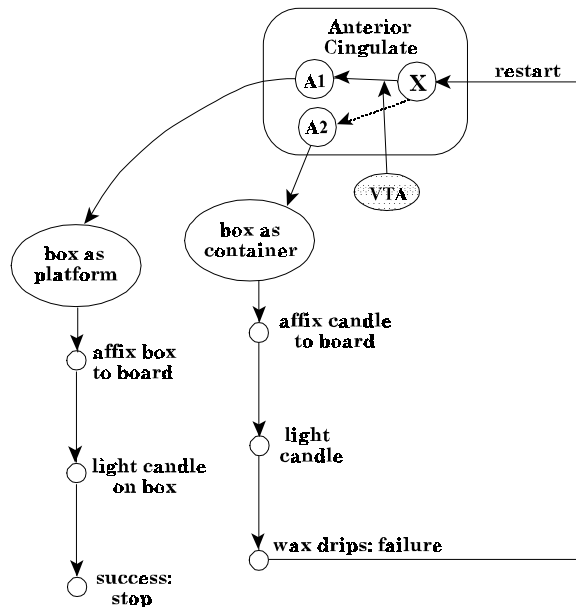


Figure 9. The computational architecture assumed by the creative problem solver connectionist network for the Duncker (1945) candle task.

who fails might try to solve the problem again. So, the Figure 9 network allows multiple attempts at a solution. It was assumed that if the subject failed to solve the problem after five attempts, then he or she would either give up or run out of time.

Ashby et al. (1996) simulated the performance of this version of the creative problem solver in the candle task — again, using the same dopamine levels for the control and positive affect conditions as in the simulations of the word association and remote associates tasks. The results are shown in Figure 10. The success rates of the creative problem solver (65% correct in the positive affect condition and 22% in the control condition) were comparable to the success rates found in the Isen et al. (1987) study (i.e., 58% correct in the positive affect condition and 13% correct in the control condition). On trials when the creative problem solver was ultimately successful, it invariably had some initial failures and succeeded only because it tried something different on a subsequent attempt (i.e., it selected more than one cognitive perspective). This same pattern characterized the positive affect human subjects in the study by Isen et al. (1987). In contrast, the control subjects were much more likely to adopt repeatedly the same perspective throughout the task, thereby attempting the same incorrect solution over and over.

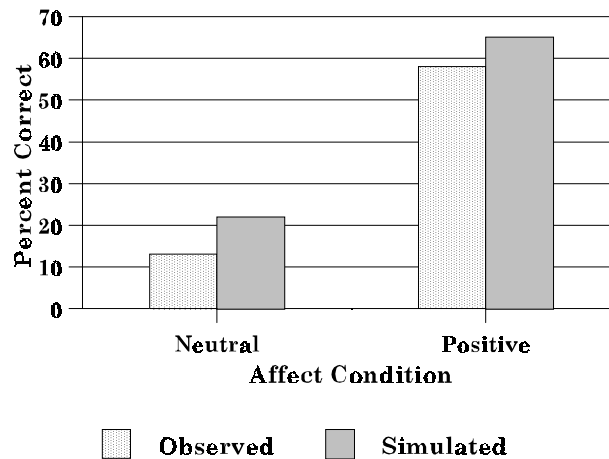


Figure 10. Success rates in the Duncker (1945) candle task observed by Isen, Daubman, and Nowicki (1987) and as simulated by the creative problem solver.

Discussion

Using the same general architecture and the same dopamine levels for all positive and neutral affect conditions, the creative problem solver mimicked the qualitative influences of positive affect on word association, the Remote Associates Test, and the Duncker's candle task. In addition, the same network successfully accounted for the effects of amphetamine on two-choice guessing.

In the applications to the three creative problem solving tasks, it should be stressed once again that the specific versions of the creative problem solver that were tested are considerable simplifications. More realistic versions would postulate the existence or potential existence of many more alternative cognitive sets or perspectives. It is also important to note that the creative problem solver makes no assumptions about whether these alternative perspectives pre-exist or whether they are constructed as the task progresses.

It should also be stressed that the present modeling attempts are limited because the data on the effects of feelings on cognition do not sufficiently constrain the model. When the creative problem solving data modeled in this section were collected, there were no theories that made specific quantitative predictions about how positive affect would influence performance in these tasks. Instead, the major interest was on *whether* there would be effects. It is possible that a number of different models could account for the word association, remote associates, and Duncker candle task data considered in this section just as well as the creative problem solver. Thus, the fact that the creative problem solver

was able to account for the major ordinal properties of these data should be considered more a demonstration of the potential of the dopaminergic theory of positive affect rather than as a rigorous test of that theory. Also, since there now is a theory that makes rigorous quantitative predictions, future experiments can collect and report data in such a way that allows more rigorous testing.

Positive affect versus arousal

Environmental conditions that induce positive affect are also likely to increase arousal. This brings to mind a number of questions. 1) Is there any difference between arousal and affect? 2) What is the neurobiological basis of arousal and how does it differ from positive affect? 3) How does arousal affect frontal cortex? 4) What are the cognitive effects of increased arousal and how do these differ from the effects caused by improved affect? This section attempts to answer these questions.

Do arousal and positive affect differ?

Early theorists defined arousal as a general state of central nervous system activity (see, e.g., Trevor, 1997). There are two common ideas about how to manipulate arousal. One is through exercise (e.g., Zillmann, 1979), and the other is by inducing an emotional state (e.g., LeDoux, 1996). Typically, this involves negative affect such as fear or anger, but according to some views, arousal increases with either positive or negative affect. Thus, if the cognitive effects of positive affect are due simply to increases in arousal, then exercise and induced negative affect should have similar effects on cognition.

Some studies have tried to test this hypothesis. For example, in two sets of experiments, positive affect subjects reported more positive affect, but not more arousal or alertness, than neutral affect control subjects, on a manipulation-check questionnaire that followed the affect induction (Isen & Daubman, 1984; Isen & Gorgoglione, 1983). In addition, the results of these experiments correlated better with the affect-induction treatments than with the reported levels of arousal. In another series of studies, Isen et al. (1987) asked four groups of subjects to solve the candle problem and to complete a subset of items taken from the Remote Associates Test. One group served as neutral affect controls. Positive affect was induced in a second group. In a third, exercise group, subjects stepped up and down on a cinderblock for 2 minutes before the test, which increased heart rate by about 60%. Finally, the fourth, negative affect group

viewed a few minutes of a depressing film (i.e., *Night and Fog*, a French documentary of the World War II German death camps). As expected, the positive affect subjects performed better than the control subjects on both the candle test and on the Remote Associates Test items. Equally important, people in the exercise and negative affect groups performed no better than the control subjects on either test. Thus, again, Isen et al. (1987) found evidence that, unlike positive affect, arousal does not improve creative problem solving.

There is other evidence against the hypothesis that the effects of positive affect on creative problem solving are due to arousal. First, current theories do not predict that arousal increases creativity, because arousal is thought to increase the likelihood of the *dominant* response, rather than of an innovative response (Berlyne, 1967; Easterbrook, 1959). Second, several authors have suggested that arousal is not a unitary construct and may need to be investigated differently from the way it has been addressed in the past (e.g., Lacey, 1967, 1975; Neiss, 1990; Venables, 1984). Third, other researchers have recently argued that arousal and pleasantness form orthogonal dimensions (e.g., Lewinsohn & Mano, 1993; Mano, 1997). On the other hand, even though they may be logically independent, pleasantness and arousal may be empirically correlated. Even so, as we will see in the next section, there is considerable evidence that arousal is associated with increased activity in neurotransmitter systems other than dopamine (e.g., norepinephrine). And, as noted, the empirical effects of arousal or negative affect are different from those of positive affect. Thus, in sum, there is substantial reason to believe that the effects of positive affect and arousal are not identical, as was once proposed (e.g., Duffy, 1934, 1941), and that the well-documented improvements in creative problem solving that occur under positive affect conditions are indeed due to the induced positive affect, and not simply to increases in arousal.

What is the neurobiological basis of arousal?

Arousal is associated with stimulation of the brain stem reticular formation (e.g., Carlson, 2001). At least four different neurotransmitters are involved, including norepinephrine (NE), acetylcholine, serotonin, and histamine (e.g., Marrocco, Witte, & Davidson, 1994; McCormick, 1992; Wada et al., 1991). Of these, probably the most attention has been given to NE.

The locus coeruleus, located in the brain stem, is the largest NE producing nucleus within the ascending reticular activating system and it releases NE to a surprisingly diverse area of the brain. The densest projections are to the hippocampus and neocortex (Ungerstedt, 1971), but it also projects throughout

the cerebral cortex, thalamus, midbrain, brainstem, cerebellum, and spinal cord (Aston-Jones et al., 1982; Foote et al., 1983). In fact, this small nucleus innervates a greater variety of brain areas than any other single nucleus yet described. Brain areas that are associated with attentional processing (e.g., parietal cortex, pulvinar nucleus, superior colliculus) receive a particularly dense NE innervation from the locus coeruleus (Morrison and Foote 1986).

Spontaneous activity of NE cells in the locus coeruleus change dramatically depending on the animal's stage of sleep and waking, with the highest firing rates occurring when the animal is awake and the lowest during sleep (Aston-Jones & Bloom, 1981; Foote et al. 1983; Jacobs, 1987). NE cells in the locus coeruleus also respond phasically to novel or noxious stimuli, including conditioned stimuli, and they may also be mildly responsive to appetitive events (Aston-Jones & Bloom, 1981; Jacobs, 1987). Repeated presentation of an initially novel stimulus causes the firing rate of NE cells to decline gradually (Aston-Jones & Bloom, 1981; Jacobs, 1987). A simple way to summarize these results is that NE cells in the locus coeruleus generally will fire to any stimulus that elicits an orienting response from the animal. If the same stimulus is presented in other conditions that do not elicit such a response (e.g., because of repeated presentation), then the locus coeruleus response will be small (Aston-Jones & Bloom, 1981; Foote et al., 1980; Grant et al., 1988).

Because of these results, Aston-Jones and his colleagues proposed that the primary function of cortical NE is to mediate vigilance (Aston-Jones & Bloom, 1981a, 1981b; Aston-Jones, Rajkowski, & Cohen, 1999). In support of this hypothesis, Aston-Jones et al. (1994) recorded from NE cells in the locus coeruleus of monkeys while they performed a vigilance task, and found that performance was best when firing rate of the NE cells was high, and that performance deteriorated when the firing rate decreased. Note that according to this hypothesis, the primary action of NE is attentional.

A similar hypothesis was put forth by Robbins (1984), who proposed that NE helps focus attention on task relevant behaviors by attenuating the influence of distracting stimuli, particularly under conditions of elevated arousal. In support of this, Carli et al. (1983) found that lesions that resulted in severely depleted levels of NE in prefrontal cortex, impaired discriminative abilities and reaction times when, and only when, bursts of loud white noise occurred during the delay period. Similar impairment was shown by Cole and Robbins (1992) when the inter-trial interval was made unpredictable in a 5-choice reaction time task. Loud noise and signal unpredictability both tend to increase arousal, thereby suggesting that NE is necessary for accurate attentional performance under arousing conditions. Related results have been found in human studies. For example,

Tafalla et al. (1997) reported that in an arithmetic task (Lundberg & Frankenhaeuser, 1976), distracting noise increased NE levels in urine during a high effort condition, but not in a low effort condition. This result also suggests that NE helps focus attention during an aroused state, so that a demanding task can be adequately performed, whereas NE is not recruited for tasks requiring low attention, so arousal can affect level of performance. Understanding the interaction between arousal, attention, and NE is thus a fundamental stepping stone to formulating neurochemical theories of attention (Coull, 1997).

How does arousal affect the function of frontal cortex?

Whether the overall effect of NE in prefrontal cortex is facilitative or disruptive depends on dose. High doses of NE applied to sensory neurons suppress neural activity (Armstrong-James & Fox, 1987; Hoffer, Siggins & Bloom, 1971; Stone, 1973), whereas low doses enhance both excitatory and inhibitory synaptic inputs (Foote, Freedman & Oliver, 1975; Kossel & Vater, 1989; Waterhouse & Woodward, 1980; Woodward, 1979). An *in vitro* study found an inverted U-shaped dose response of NE on glutamate-evoked discharges in sensory cortical neurons (Devilbliss & Waterhouse, 1996). This U-shape corresponds to behavioral data in which locus coeruleus NE discharge was measured during a sustained attention task. The level of NE correlated with performance, such that performance was poor at low and high levels of NE, and good at intermediate levels (Rajkowski et al., 1992).

One explanation of the nonmonotonic effect of NE dose on performance comes from studies of specific NE receptor types. There are two distinct classes of NE receptors, called α and β receptors. Suppressant effects of NE have been shown to be mediated by β receptors, although this inhibitory effect has not been tied to working memory performance. On the other hand, the α receptors seem most important for arousal's effect on prefrontal cortex. Within the class of α receptors, there are two different subtypes, denoted α_1 and α_2 , and there is now good evidence that they have opposing effects on prefrontal cortical function. In particular, activation of α_2 receptors appears to have a facilitative effect, whereas activation of α_1 receptors seems to impair prefrontal cortical function.

A variety of studies support the hypothesis that α_2 receptor activation facilitates prefrontal cortical functioning. For example, in both rats and monkeys, α_2 agonists improve performance on a variety of working memory related tasks that are known to depend on the prefrontal cortex, including delayed response (Arnsten et al., 1988), delayed match-to-sample (Jackson & Buccafusco, 1991),

and delayed alternation (Arnsten & Goldman-Rakic, 1985, Carlson et al., 1992). Such results are even more pronounced in elderly animals, which is especially significant because NE levels in prefrontal cortex decrease dramatically with age (Arnsten, 1997; Gaspar et al., 1989, 1991). On the other hand, these same α_2 agonists have little effect on memory tasks that are primarily mediated outside of prefrontal cortex (PFC), including recognition memory and reference memory (Arnsten & Goldman-Rakic, 1985, 1990).

Arnsten and Contant (1992) hypothesized that α_2 agonists benefit delayed response performance by reducing interference from distracting stimuli. A selective α_2 agonist (i.e., clonidine) improved performance in a delayed response task when the delay period was free of distractors, but the drug was most effective when distracting noise was present (Jackson & Buccafuso, 1991; Arnsten and Contant, 1992). These findings are consistent with NE depletion increasing distractibility (Roberts et al., 1976; Carli et al., 1983) emphasizing the importance of NE mechanisms in attention regulation.

Although α_2 agonists have a generally beneficial effect on prefrontal cortical function, the story is quite different for α_1 agonists. A number of recent studies have shown that low doses of α_1 agonists (e.g., cirazoline, phenylephrine) impair spatial working memory in rats and monkeys (Arnsten & Jentsch, 1996; Steere et al., 1996).

If NE binds to both α_1 and α_2 receptors and the actions through these two receptor types have conflicting effects, then why don't these opposite effects just cancel out? One possible answer to this important question comes from pharmacological studies of NE binding. Such studies show that NE has a higher affinity for α_2 receptors than for α_1 receptors (Arnsten, 1997). Therefore, for small increases in NE, the effects of α_2 activation will dominate the effects of α_1 activation, and the overall effect of NE in prefrontal cortex will be facilitative. As NE levels increase, the effects of α_1 receptor activation will also increase, and eventually the overall effect of NE will be to impair prefrontal cortical function. Of course, these effects perfectly mimic the well-known Yerkes-Dodson (1908) effect, in which small and moderate increases in arousal improve performance but large increases have a detrimental effect.

As discussed above, α_2 receptor activation appears to facilitate prefrontal cortical function. Given this, the next important question is to ask how this facilitation occurs. As with dopamine, the action of NE on prefrontal cortex is thought mainly to be modulatory. In particular, many results suggest that NE does not transmit specific moment-to-moment details. Rather, it appears to alter the efficacy of the major excitatory and inhibitory neurotransmitters (glutamate and GABA, respectively) (Jiang et al., 1996; Kasamatsu & Heggelund, 1982;

Kossel & Vater, 1989; McLean & Waterhouse, 1994; Waterhouse et al., 1990).

Perhaps the most popular model of the neuromodulatory effects of NE is that a constant low level administration of NE increases the signal-to-noise ratio of synaptically mediated responses (e.g., Foote, Freedman & Oliver, 1975; Waterhouse, Moises, Woodward, 1980; Waterhouse & Woodward, 1980). Such relative enhancement of responses to strong inputs relative to low-level or basal activity has been found in several locus coeruleus target areas including cerebral cortex, hippocampus, midbrain, thalamus, and spinal cord (for a review see Aston-Jones et al., 1991; Foote et al., 1983), and is consistent with recent neural modeling work hypothesizing that NE acts to enhance signal-to-noise ratios in target systems (Servan-Schreiber et al., 1990).

The contribution of other neurotransmitters to arousal

As mentioned above, in addition to NE, other neurotransmitters have been implicated in the control of arousal, especially acetylcholine (ACh), serotonin (5-HT), and histamine. The release of all three of these neurotransmitters is closely tied to the sleep-wake cycle, with release increasing as the animal becomes more active (e.g., Day, Damsma, & Fibiger, 1991; Steininger et al., 1996; Trulson & Jacobs, 1979).

ACh has some of the same effects as (low doses of) NE on prefrontal cortical function. In particular, working memory is facilitated by drugs that enhance cholinergic activity and impaired by drugs that block the action of ACh (Dawson & Iverson, 1993; Glasky et al., 1994; Robbins et al., 1997). Also, like NE, ACh increases the signal-to-noise ratio of individual cortical neurons (Drachman & Sahakian, 1979; Hasselmo, 1995; Sato, Hata, Masui, & Tsumoto, 1987), and some recent evidence suggests it does this both by boosting the signal and decreasing the noise (Furey, Pietrini, & Haxby, 2000). The basal forebrain cholinergic cells seem to be particularly influenced by conditioned visual stimuli and by reinforcers, but also by aversive air-puffs (Wilson & Rolls, 1990; Richardson & De Long, 1990).

What are the cognitive effects of increased arousal and how do these differ from the effects caused by improved affect?

We have already discussed evidence that in the case of creative problem solving, positive affect and arousal seem to make contrasting predictions. First, we

reviewed much data suggesting that positive affect improves creative problem solving. We also discussed a more restricted set of data that failed to find any effect of arousal on creative problem solving (Isen et al., 1987). This latter result is consistent with theories of arousal that predict arousal increases the likelihood of the *dominant* response, rather than of an innovative response (Berlyne, 1967; Easterbrook, 1959). If one is attacked by a predator, then the dominant response (e.g., to flee) is frequently adaptive, but in tests of creative problem solving, an innovative response is usually more likely to succeed.

On the other hand, it appears that in the case of working memory, positive affect and arousal make similar predictions. In particular, dopamine, NE, and ACh released into prefrontal cortex all have similar effects on performance in working memory tasks – at low or moderate doses they are facilitative, but at high doses they impair performance. Thus, if positive affect leads to increased dopamine release in frontal cortex and arousal is associated with increased release of NE and ACh, then mild to moderate levels of positive affect and arousal should both improve working memory. In contrast, extreme levels of positive affect or arousal should impair working memory. To our knowledge, these predictions are largely untested.

It is difficult to make specific predictions about how the effects of arousal and positive affect might differ in other cognitive tasks. From a theoretical perspective, one of the problems is that many of the neural effects appear to be similar (e.g., increasing signal-to-noise ratio). In addition, positive affect and arousal often co-occur. It is not difficult to predict that before much progress occurs in this area, a much more extensive data-base must be collected (especially behavioral data).

Conclusions

The dopaminergic theory of positive affect that was proposed by Ashby et al. (1999) assumes that during periods of mild positive affect, there is a concomitant increased dopamine release, primarily in the mesocorticolimbic system. The theory further assumes that the resulting elevated dopamine levels in anterior cingulate increase cognitive flexibility and facilitate the selection of cognitive perspective or set, thereby improving creative problem solving ability. Note that this theory does not assume that positive affect simply turns dopamine on or off. Instead, it is assumed that moderate levels of dopamine are present even under neutral affect conditions. The induction of mild positive affect is assumed only to increase slightly these normal dopamine levels.

A computational version of the theory was described that takes the form of a connectionist network called the creative problem solver. Standard pharmacological techniques were used to derive the theoretical effects of dopamine on the activation function of units in the portion of the network that corresponds to the anterior cingulate. The network successfully accounted for the effects of amphetamines on a two-choice guessing task and it accounted for the effects of positive feelings on three creative problem solving tasks (word association, the Remote Associates Test, and Duncker's candle task). Although the focus of this chapter was primarily on positive affect, the creative problem solver provides a general model of creative problem solving that could be used to model data from many different experimental tasks and collected from a variety of different subject populations. In addition, the model makes specific predictions about the effects on creative problem solving of any experimental factor that systematically alters cortical dopamine levels. Thus, the potential contribution of the model is considerably greater than the rather narrow applications considered here.

We also briefly discussed the neurobiological basis of arousal. This is important because arousal often seems to co-occur with states of positive affect. Because of this empirical correlation, a complete understanding of the cognitive effects of positive mood requires an accurate theory of arousal.

Author Notes

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Notes

1. These were not the same dopamine levels as assumed in the simulations of the saline and amphetamine conditions of the two-choice guessing task. There is no reason to expect a 10 mg dose of amphetamine to cause the same increase in brain dopamine levels as the giving of a small unanticipated gift. Also, intravenous infusion of saline could alter mood, especially since the Ridley et al. (1988) experiment was double blind. Thus, it seemed reasonable to assume that the dopamine levels in the Ridley et al. saline group might differ from the dopamine levels in the neutral affect groups of the Isen creative problem solving studies.

2. At this point, the only free parameter is the dopamine level associated with the positive affect group. However, manipulating this parameter confers little flexibility since the same dopamine level was

assumed for the positive affect conditions in all three creative problem solving applications (i.e., word association, the Remote Associates Test, and the Duncker candle task).

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Appendix

The creative problem solver connectionist network

This appendix describes the details of the Ashby et al. (1996) simulations of the creative problem solver under high and low dopamine level conditions in the four tasks described in the chapter. In each simulation, the two experimental conditions were assumed to differ only in dopamine level, and this difference was instantiated via the activation function described in Equations 2 - 4. The activation function parameters, K_{NMDA} and θ were fixed at the values 1 and 2, respectively. The parameters $K_{\text{E}}(\text{DA})$ and $K_{\text{AMPA}}(\text{DA})$ were assumed to vary with dopamine level. Numerical values for these parameters were selected via trial-and-error. A single value of $K_{\text{E}}(\text{DA})$ was chosen for the word association, remote associates, and the candle tasks, since the experimental manipulation was identical in all three (i.e., $K_{\text{E}}(\text{DA}) = 1.25$ for the positive affect conditions, and

$K_E(\text{DA}) = 5$ for the neutral affect conditions). The value of $K_{\text{AMPA}}(\text{DA})$ was set arbitrarily to $1/K_E(\text{DA})$ in all simulations (i.e., therefore, $K_{\text{AMPA}}(\text{DA}) = 0.8$ for the positive affect conditions, and $K_{\text{AMPA}}(\text{DA}) = 0.2$ for the neutral affect conditions). For the two choice guessing task, in which dopamine levels were manipulated by amphetamine administration, different values were used ($K_E(\text{DA}) = K_{\text{AMPA}}(\text{DA}) = 1.0$ for the amphetamine group, and $K_E(\text{DA}) = 2.5$ and $K_{\text{AMPA}}(\text{DA}) = 0.4$ for the saline group).

The weights between all nodes in the semantic networks (i.e., see Figures 5 and 7) were chosen so that the performance of the creative problem solver matched the performance of the neutral affect control subjects (see text for more details). Each cognitive set unit (e.g., P1 and P2 in Figure 1) was assigned an initial bias or salience. Let B_i denote the salience of cognitive set P_i . For example, in Figure 7, the set or perspective *Semantic Relations* was assigned a higher salience than the set *Compound Words*.

The selection operation performed by the anterior cingulate was modeled in the following way. First, one of the anterior cingulate units A_i (where $i = 1$ or 2 in all simulations except word association, where $i = 1, 2,$ or 3 ; i.e., see Figures 5, 7, and 9) was selected randomly (according to a uniform distribution). Second, unit X generated a value of random magnitude (denoted by \mathbf{X} and normally distributed with a mean of 2 and a variance of 1). The connections between node X and nodes A_i are modulated by dopamine (i.e., see Figure 1), so the third step was to treat \mathbf{X} as the input to the activation function shown in Equations 2 - 4 (i.e., so $\sum w_{ik}a_i = \mathbf{X}$). Call this output activation value $act(\mathbf{X})$. Fourth, the net input activation of cognitive set unit P_i was:

$$act(P_i) = B_i + act(\mathbf{X})$$

if unit A_i was selected in step 1. Otherwise,

$$act(P_i) = B_i.$$

Finally, unit P_i became the active cognitive set if

$$act(P_i) = \max[act(P_1), act(P_2), \dots, act(P_n)],$$

(where n is the total number of alternative cognitive set units). Each cognitive set unit projected to a different semantic network (i.e., see Figures 5, 7, and 9). The weights between every pair of nodes in semantic networks associated with inactive cognitive sets were all set to zero. To generate model predictions, 100 simulations were run for each condition of each task.

For the two-choice guessing task, the initial values for the salience parameters were set to 0 for each response (i.e., $B_1 = B_2 = 0$). At the end of each trial, the salience for the emitted response was updated. If the response was reinforced (i.e., correct), the salience was increased by 0.35, otherwise it was decreased by the same amount. If this method produced a negative value, the salience was set to 0. Stimulus generation procedures were the same as used by Ridley et al. (1988).

The word association and remote associates tasks were simulated using the

architectures shown in Figures 5 and 7. For the word association network, the initial salience of the cognitive set *part of the hand* was set to 0.15, the salience of *use of the hand* was set to 0, and the salience of *compound words* was set to 0.35. For the remote associates network, the initial salience of the cognitive set *semantic relations* was set to 0.55, and the salience of *compound words* was set to 0.2. For both networks, the weights between every pair of nodes in the semantic network is shown in Table 1. In both tasks, the activation values of the nodes representing the stimulus words were set at 1 on each trial, and the activation function for each node in the semantic networks was linear. The probability that the word represented by any given node would be chosen for that trial was determined by dividing the activation level of that node by the sum of the activations of all words in the semantic network.

For the candle task, the architecture shown in Figure 9 was used. The initial salience of the cognitive set *box as a container* was 0.3 and the initial salience of *box as a container* was 0. As described in the text, a trial was considered a failure only if the network failed to solve the problem on five successive attempts.

Table 1. Weights between Word Nodes in the Semantic Network Portion of the Creative Problem Solver Network.

Word Association		Network		Remote Associates	
Word Pair	Weight	Word Pair		Word Pair	Weight
palm-basketball	0.3	club-party			1.1
palm-steal	0.6	gown-dress			0.6
palm-lift	0.5	mare-horse			0.1
palm-sweaty	0.2	club-dance			0.2
palm-hand	0.7	gown-dance			0.2
hand-finger	0.4	club-golf club			0.5
palm-palm reader	0.9	golf club-golf			1.0
palm-palm tree	0.3	gown-wedding gown			1.0
palm tree-Hawaii	0.2	wedding gown-wedding			1.0
		club-nightclub			0.6
		nightclub-night			1.0
		gown-nightgown			0.6
		nightgown-night			1.0
		mare-nightmare			0.6
		nightmare-night			1.0